

RESEARCH ON MILK HOMOGENIZATION IN THE STREAM HOMOGENIZER WITH SEPARATE CREAM FEEDING

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ABSTRACT

Homogenization, which is used in the technological schemes of production of most dairy products, is the most energy-intensive of the processes of mechanical processing of milk. One promising way to increase the energy efficiency of homogenization is to use separate homogenization and to use a little-researched stream homogenizer with separate cream feeding. The principle of its action is to pre-divide milk into cream and skim milk, and feed the fat phase with a thin stream into the stream of skim milk. This creates the conditions for achieving the high value of the Weber criterion – the main factor in the dispersion of milk fat. The purpose of these researches is to conduct experimental studies and determine the energy consumption and quality of homogenization of milk after treatment in a stream homogenizer. To achieve this goal, a designed experimental setup was used. The dispersive indices of the milk emulsion were determined by computer analysis of micrographs of milk samples obtained with an optical microscope and a digital camera using Microsoft Office Excel and Microsoft Visual Studio C # software using the OpenCV Sharp library. As a result of experimental studies, the critical value of the Weber criterion for homogenization of milk was determined, which is 28. The regularities of dispersion of milk fat in a stream homogenizer with separate feeding of the fat phase have been established. It is determined that the milk treatment in the experimental homogenizer allows us to achieve an emulsion with an average size of fat globules of about 0.8 μm (at the level of valve homogenizers). The value of the homogenization coefficient is obtained for the disruption of the fat globule in the conditions: subject to a single effect on the emulsion, without the influence of vibration and cavitation. This homogenization coefficient equals $3300 \text{ m}^{3/2} \cdot \text{s}^{-1}$.

Keywords: milk; homogenization; homogenizer; stream homogenizers with separate cream feeding

INTRODUCTION

Today, the vast majority of milk as raw materials for the production of drinking milk, cream and other types of dairy products is homogenized (Rayner and Dejmek, 2015). The main advantages of products manufactured using homogenization: providing uniformity of color, taste, fat content; improving the consistency, increasing the intensity of the white color, increasing the stability during storage, reducing the settling of fat and creating a fuller taste of the product.

But homogenization is one of the most energy-consuming processes in the vast majority of technological schemes for dairy production. The specific energy consumption of the most commonly used valve homogenizers reaches $8 \text{ kW} \cdot \text{h} \cdot \text{t}^{-1}$ and is the largest of the milk processing equipment (Yong, Islam and Hasan, 2017a; Ashokkumar, Rink and Shestakov, 2011).

As a result of attempts to solve the existing disadvantages of homogenization, scientists have developed a wide range

of homogenizers, such as valve, pulsation, vacuum, stream, ultrasonic, rotary, etc. However, none of them combines a high degree of grinding milk fat globules (such as valves) with low energy consumption (Narvhus, Abrahamsen and Østlie, 2007; Yong, Islam and Hasan, 2017b).

The main reason for such problems is the lack of a unified theory and mechanism of dispersion of the fine-phase phase of fat emulsions and difficulties in obtaining experimental visual data of the process of disruption of fat particles of microscopic size.

Recent visual data on the process of fat phase dispersion in valve homogenizers confirm the validity of the turbulent viscous theory according to which the disruption occurs as a result of the destabilization of Kelvin – Helmholtz and Rayleigh – Taylor (Håkansson et al., 2011; Håkansson et al., 2010; Innings and Trägårdh, 2005; Loitsyansky, 2003). Despite the significant differences between these hypotheses, they are common to create hydrodynamic

conditions in the fracture zone that contribute to the increase of the relative velocity of the emulsion phases. That is, the universal criterion for deformation and disruption of the fat globule is the Weber criterion (We), the main reason for dispersion being the difference in velocity between the fat globule and the surrounding plasma (relative velocity of phases or velocity of sliding of the fat globule) (Håkansson et al., 2013).

The simplest and most obvious way to create a sliding fat globule is to separate milk fat from whole milk and feed it with a thin stream or film into the product's high-velocity stream of skim milk. This method is the basis for the construction of a stream homogenizer with separate cream feeding (SHSCF), in which the milk cream is fed by a thin stream perpendicular to the flow of skim milk (Figure 1) (Deinychenko, Samoichuk and Kovalyov, 2016).

Additional intensification of the process of homogenization in such devices is due to the concentration of the supplied energy on the fatty phase of the emulsion using separate homogenization. Preliminary separation of milk into cream and skim milk and treatment of only the fat phase, which results in the reduction of the volume of the emulsion being processed, which leads to the proportional reduction of energy consumption (Dhankhar, 2014; Samoichuk and Kovalyov, 2015).

Due to the selection of structural-technological and mode parameters it is possible to combine the normalization of milk fat content with the operation of homogenization.

Therefore, the purpose of the study is to determine the prospects of using a stream homogenizer with separate cream feeding for milk processing by experimentally determining the quality of homogenization and energy consumption.

Scientific hypothesis

The scientific hypothesis is the ability to solve the problem of high energy consumption for homogenization of milk by using a stream homogenizer with separate cream feeding. In such a homogenizer, when the fat fraction is fed into the stream of skim milk, a high difference of phase velocities is created between the dispersed and dispersive phases of the emulsion, which makes it possible to achieve higher values of the Weber criterion than in other types of homogenizers.

MATERIAL AND METHODOLOGY

Experimental equipment

For the experimental research of the SHSCF, an installation was developed, the scheme of which is presented in Figure 2 (Samoichuk and Kovalyov, 2011; Samoichuk and Kovalyov, 2013).

Skim milk goes through the pipeline from the container 2 through the pump 1 into the homogenization chamber 4. From the tank for cream 12, with the pump 7 through the channel 11, the fat phase is supplied to the central zone of the homogenization chamber in the stream of skim milk, where the process of dispersion takes place.

To increase the flow of skim milk in the homogenization chamber, stream guides 5 made of stainless steel were installed, which are secured by hinges 10 and have adjustable rods to adjust the distance between the guides. The housing of the homogenization chamber is made of organic glass for process monitoring. A gauge 3 is required to control the fluid pressure values. In the container 2 there is an opening for draining the residues of the product. The finished product is poured into the container 8.

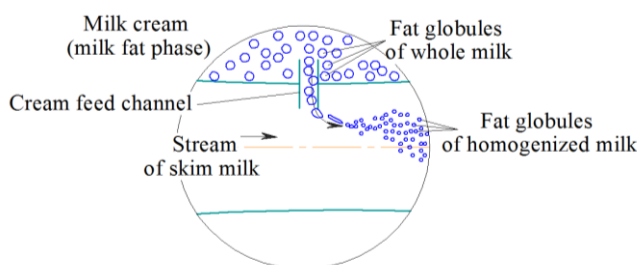


Figure 1 Scheme of homogenization in a stream apparatus with separate cream feeding.

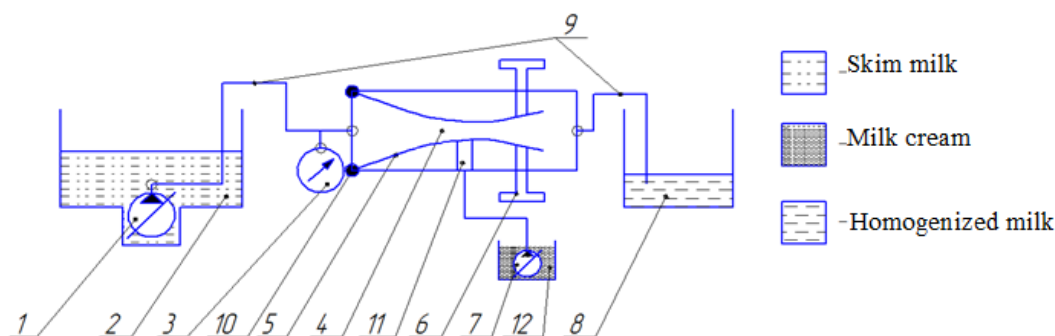


Figure 2 Scheme of the laboratory unit of the SHSCF. Note: 1 – rotor type pump; 2 – container for skim milk; 3 – pressure gauge; 4 – homogenization chamber; 5 – guides; 6 – adjusting rods; 7 – pump of supply of the fat phase; 8 – container for receiving the finished product; 9 – pipelines; 10 – hinges; 11 – feed cream channel; 12 – tank for cream.

Prior to submission to the SHSCF, the milk is divided into skim milk and cream. Skimmed milk is fed under pressure at a certain rate, which increases in the central area of the device due to the narrowing of the flow, the value of which can be adjusted by rods. In the place of greatest narrowing, cream is supplied through a thin channel which diameter is 0.6 – 0.8 mm (Samoichuk and Kovalyov, 2013; Samoichuk, Kovalyov and Sultanova, 2015). The channel of such a small diameter creates minimal flow resistance and allows the flow of cream with a thin stream. By varying the flow velocity in the cream feed zone, the distance from the end of the cream feed channel to the edge of the narrowing channel and the cream supply it is possible to investigate their effect on the quality and energy consumption of the milk fat dispersion process.

Figure 3 presents a general view of the laboratory unit for studying SHSCF.

In the central part of the chamber 3 (Figure 3), at the place of maximum narrowing, radial channels for feeding the fat phase are made.

Thus, thin streams of cream are fed into the high-velocity stream of skim milk, which creates the conditions for high-efficiency dispersion of milk fat – a high difference in velocity of phases (velocity of sliding the fat globule relative to the dispersion medium), which by Weber's criterion is the main parameter of the disruption of fat globules of milk.

The main parameter that determines the dispersion of the milk emulsion after treatment in SHSCF (Figure 4) is the relative velocity of the dispersed and dispersive phases, which is most influenced by the velocity of skim milk stream v_{sm} , the velocity of the flow of cream v_c , the diameter of the feed channel of cream d_c and its fat content F_c .

For the experimental studies, whole milk was used (DSTU 8553:2015). Density 1027 – 1023 kg.m⁻³, fat content 2.5 – 4.4%.

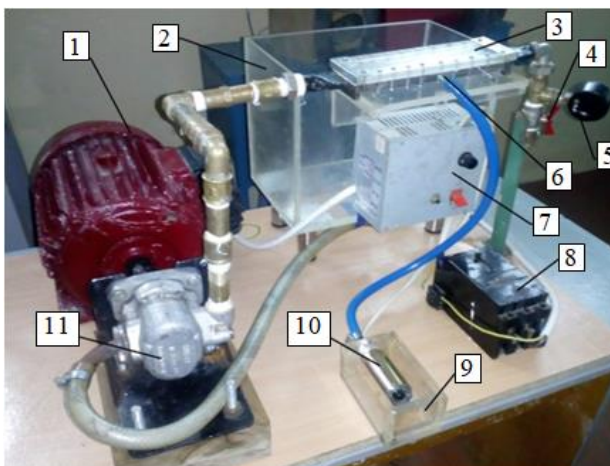


Figure 3 Structure of the laboratory unit for studying SHSCF. Note: 1 – electric motor; 2 – container for skim milk; 3 – homogenization chamber; 4 – throttle valve; 5 – pressure gauge; 6 – cream feed channel; 7 – control unit for the cream feed pump; 8 – electric starter of the main engine; 9 – tank for cream; 10 – pump for feeding cream; 11 – skim milk feed pump.

The average diameter of the fat globules of the emulsion (d), which should be provided as a result of homogenization, is 0.8 – 1.2 μm , which is sufficient for modern technological processes of milk processing.

The temperature of homogenization of milk was provided within the range of 60 – 65 °C. Numerous studies show that this temperature is optimal for the dispersion process. The minimum surface tension of the fat globule and the viscosity of the milk is ensured, the fat fractions go into the liquid state and no undesirable changes of properties occur under the action of high temperature (Ion-Titapiccolo, Alexander and Corredig, 2013).

Statistical analysis

The dispersive indices of the milk emulsion were determined by computer analysis of micrographs of milk samples obtained with an optical microscope and a digital camera Mustek Wcam 300 (resolution 640 x 480). Each experiment was repeated 3 times. From each experiment, 3 samples were selected and 2 dilutions were prepared from each sample. 6 characteristic microscope field of view photos were selected from each dilution. Thus, 36 microscope fields of view were analyzed to determine statistical characteristics of milk.

The method of analysis of geometric characteristics of fat globules based on digital image analysis technologies was used to analyze the obtained micrographs.

The number of fat globules in the microscope field of view and their diameter were determined in the process of calculations. The average diameter of the fat globule was determined by the statistical method of power average (arithmetic mean).

For this purpose, the software module has been developed that is implemented in Microsoft Visual Studio 2013 based on C # using the OpenCV Sharp library set 4.2.0. The exported numerical data and the calculation of the sample statistics were performed in Microsoft Office Excel 2013. McBrain VA 318 electric wattmeter (Volga region plant of power equipment, Russia) was used to record power.

RESULTS AND DISCUSSION

Determination of the influence of the velocity of skim milk and the distance between the guides on the dispersion of milk emulsion

The main influential factor in the dispersion of the fat phase in the SHSCF is the rate of flow of skim milk, the change of which was varied by the supply of skim milk Q_{sm} . The results of the experimental studies and their comparison with the theoretical ones by the formula (Samoichuk and Kovalyov, 2013; Samoichuk, 2018) are shown in Figure 5.

As shown by the obtained data, the change in the distance between the guides (the area of intersection of the working chamber) has virtually no effect on the dispersion of the milk emulsion, which is consistent with the results of theoretical studies (Samoichuk and Kovalyov, 2013; Samoichuk, 2018).

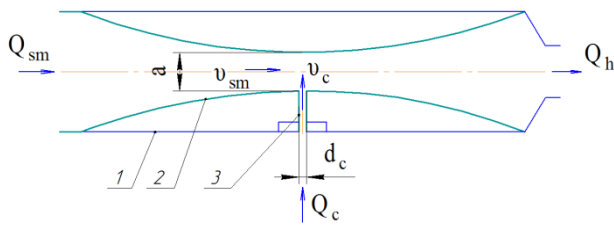


Figure 4 Calculation scheme of SHSCF. Note: 1 – chamber of stream homogenizer of milk; 2 – guides for the formation of a stream of skim milk; 3 – cream feed channel; a – distance between the guides; Q_{sm} , Q_c , Q_h – supply of skim milk, cream and productivity of SHSCF, $m^3 \cdot s^{-1}$.

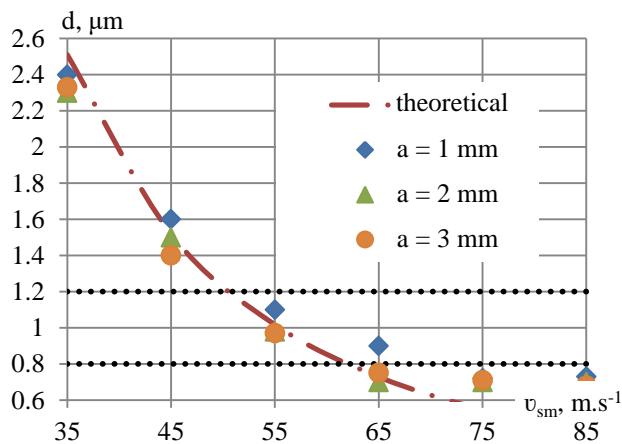


Figure 5 The dependence of the average diameter of fat globules d on the distance between the guides of SHSCF a and the velocity of skim milk v_{sm} at $d_c = 0.7$ mm, $v_c = 80$ $m \cdot s^{-1}$, $F_c = 30\%$.

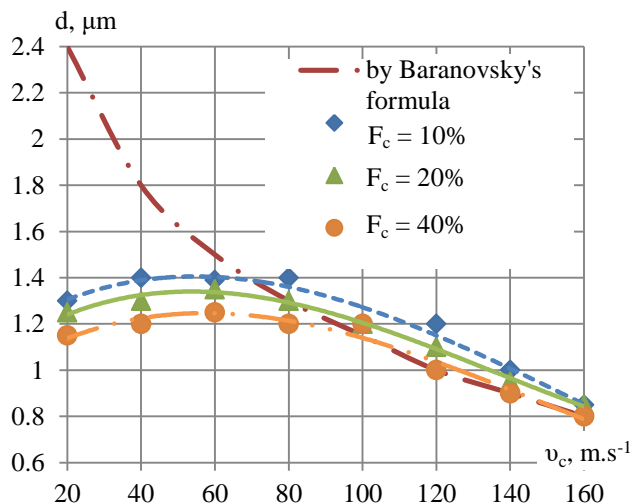


Figure 6 The dependence of the average diameter of fat globules d on the velocity of the flow of cream v_c SHSCF and fat content F_c (at $v_{sm} = 60$ $m \cdot s^{-1}$).

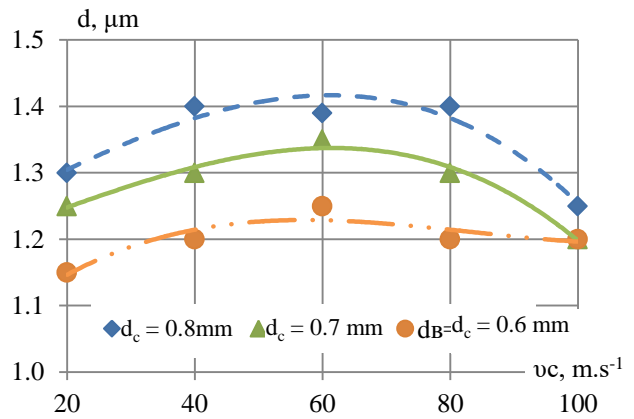


Figure 7 Dependence of the average diameter of the fat globules d on the velocity v_c and the diameter of the feed channel of dairy cream d_c SHSCF (at $v_{sm} = 60$ $m \cdot s^{-1}$).

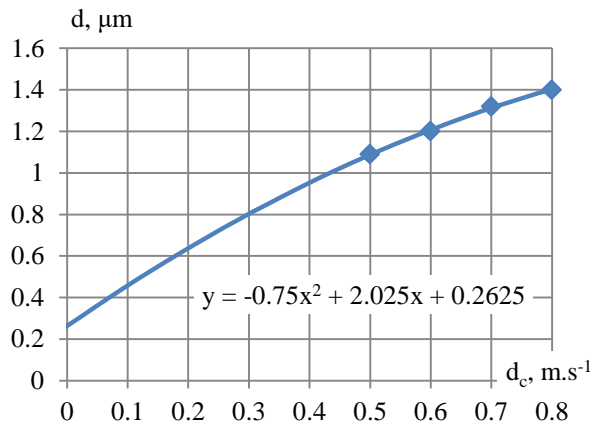


Figure 8 Prediction of the average size of fat globules of milk d for $d_c < 0.5$ mm.

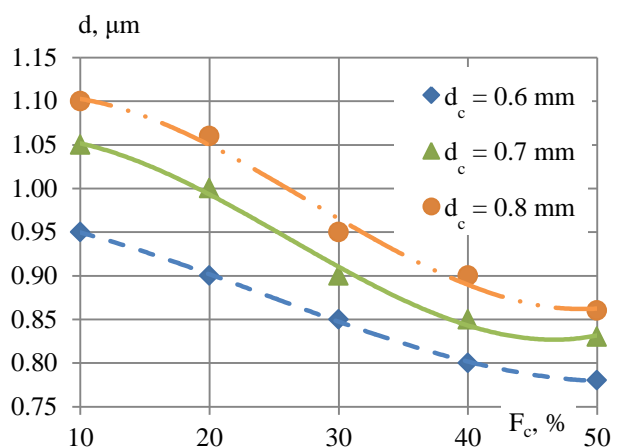


Figure 9 The dependence of the average diameter of the fat globules d on the diameter of the feed channel d_c SHSCF and cream fat F_c (at $v_{sm} = 80$ $m \cdot s^{-1}$).

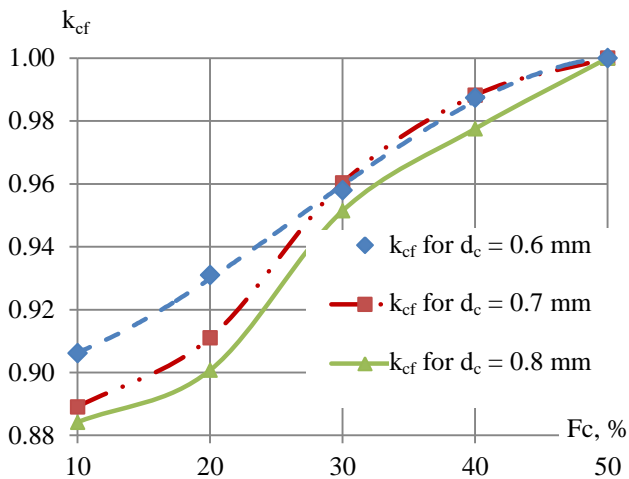


Figure 10 The dependence of the fat coefficient of cream for SHSCF k_{cf} on the fat content F_c , % (at $v_{sm} = 80 \text{ m.s}^{-1}$).

The slight increase in the size of the fat globules at $a = 1 \text{ mm}$ (by 2 – 5%) is explained by the increase in the Reynolds coefficient and the fluid turbulence. Increasing turbulence can be the cause of inefficient power dissipation, which is consistent with the results of the stream apparatus study (Abiev, 2000). For SHSCF, the main factor in the disruption of fat globules is the sliding velocity of the fat globules, which increases as the flow rate of skim milk increases. To obtain an average size of fat globules of $0.8 \mu\text{m}$, it is necessary to provide a skim milk velocity of $60 - 65 \text{ m.s}^{-1}$.

The experimental data are in good agreement with the theoretical data at critical Weber number $We_k = 130$, coefficient of SHSCF (Samoichuk, 2018) $k_c = 0.7$ in the range of $35 < v_{sm} < 70$. However, the true critical Weber number can only be calculated after the experimental determination of the stream dispersion coefficient.

At a velocity of more than 70 m.s^{-1} , the dispersion is hardly increased. Similar is the graph of the dependence of the dispersion on the pressure for the valve (Rovinsky, 1994; Loncin and Merson, 1979), pulsation homogenization with a vibrating rotor (Samoichuk et al., 2016) and flow-stream (Samoichuk, 2018) homogenization, which testifies to the similarity of the mechanisms of dispersion of fat globules in them.

Determination of effect of stream dispersion coefficient on average size of fat globules in milk

The use of higher fat cream increases the dispersion of the homogenized emulsion (Figure 6). This is due to the increase in the velocity of sliding fat globules of cream due to the decrease in the amount of plasma fed together with the cream. The dashed line shows the relationship between the size of the fat globules and the velocity of the cream in the disruption of the fat globules similar to the valve homogenization according to the formula by N. V. Baranovsky (Rovinsky, 1994). If $v_c > 80 - 100 \text{ m.s}^{-1}$, the valve dispersion is the dominant principle of dispersion – the value of dispersion is close to that calculated by Baranovsky's formula.

In the range of $40 < v_c < 80$, the sizes of fat globules are maximal, and at $v_c < 30 \text{ m.s}^{-1}$ they are reduced by 6 – 10% (Samoichuk, 2018). The decrease in dispersion at the

velocity of the stream of cream more than 30 m.s^{-1} can be explained by the presence of a steady stream of cream, which is destroyed only at the chamber wall which is opposite to the location of the channel of the cream. In this zone, the velocity of the skim milk stream is minimal, which results in lower values of the flow rate of fat globules.

If you do not take into account the dispersion of the type of valve homogenization, which is energy inefficient (in the range of $20 < v_c < 80 \text{ m.s}^{-1}$), the highest degree of homogenization in SHSCF can be achieved at $v_c < 20 \text{ m.s}^{-1}$. By predicting with Excel spreadsheet tools at $v_c < 5 - 10 \text{ m.s}^{-1}$, the coefficient of influence of the flow velocity of the cream, SHSCF has a maximum value $k_v = 1$. At $40 < v_c < 80$ $k_v = 0.75 - 0.80$, and at $20 < v_c < 40$ $k_v = 0.8 - 0.85$.

Reducing the diameter of the cream channel leads to a decrease in the size of fat globules of milk (Figure 7).

This is due to the decrease in the central zone of the cream stream with a reduced flow rate of fat globules. Reducing the diameter of the channels from 0.8 to 0.6 mm leads to an increase in the dispersion by 8 – 10%. It is logical to assume that the maximum flow rate can be obtained by entering only one fat globule into the stream of skim milk. The maximum value of the coefficient of influence of the diameter of the channel of the fat phase will be at $d_c = d$. But testing this assumption in practice is difficult. The prediction made by Microsoft Excel (Figure 8) shows that at $d_c = d$ the average size of fat globules is 0.26 microns, therefore the coefficient of cream feed channel diameter $k_{cd} = 1$ at $d_c = 0.26 \text{ mm}$.

Then the formula for the definition of k_{cd} looks like

$$k_{cd} = \sqrt{\frac{0.26}{2.025d_c - 0.75d_c^2 + 0.2625}} \quad (1)$$

Example: at $d_c = 0.6 \text{ mm}$ $k_{cd} = 0.46$; at $d_b = 0.7 \text{ mm}$ $k_{cd} = 0.44$; at $d_b = 0.8 \text{ mm}$ $k_{cd} = 0.43$.

The graph of the dependence of the dispersion of the emulsion on the fat content of the cream (Figure 9) indicates a decrease in the rate of decrease in the size of fat globules with increasing fat content of cream (Samoichuk, 2018).

When the fat content of the cream is more than 40%, the dispersion of the emulsion is almost not reduced. The predicted minimum dispersion of milk is reached at $F_c = 45 - 55\%$, where the coefficient $k_{cf} = 1$. For other values of the fat content of cream k_{cf} of the SHSCF are shown in the graph (Figure 10). In the range of $F_c > 30\%$, the values of the fat coefficient of stream dispersion do not differ for different d_c . At $F_c < 30\%$ a significant effect is caused by the high turbulence of the flow and the mechanisms of disruption associated with the disruption of turbulent vortices, thus values of k_{cf} for $d_c = 0.8 \text{ mm}$ increase by 2 – 4% compared with $d_c = 0.6 \text{ mm}$.

Therefore, to increase the degree of dispersion it is necessary to reduce the diameter of the feed channel of cream, use cream with a fat content of 30 – 50% and provide a feed rate of cream less than $30 - 40 \text{ m.s}^{-1}$ or more than $80 - 100 \text{ m.s}^{-1}$.

Thus, for the data shown in Figure 6, the coefficient of stream dispersion will be equal (at $k_{cd} = 0.44$; $k_v = 0.75$; $k_{cf} = 0.96$) $k_c = 0.44 \times 0.75 \times 0.96 = 0.32$.

The critical Weber number corresponding to the experimental data is $We_k = 28$. Compared to opposite-flow stream homogenization ($We_k^c = 500$ (Samoichuk, 2008)), this value is much smaller. But a direct comparison of these values is incorrect due to the use of the modified Weber criterion for opposite-flow stream homogenization – that is such We_k , where instead of the velocity of the sliding of the fat globule, the flow rate of the milk emulsion is used.

According to the obtained data of the critical value of the Weber criterion and (Samoichuk, 2018; Samoichuk et al., 2019), the homogenization coefficient for SHSCF will be

$$K_h = \sqrt{\frac{28 \times 0.024 \times 0.1^3}{8 \times 980}} \sqrt{\frac{6}{3.14}} = 3.300 \times 10^{-6} \text{ m}^{3/2} \cdot \text{s}^{-1}.$$

The importance of the obtained results is that this value is obtained for the disruption of the fat globule in "pure" conditions: subject to a single effect on the emulsion, without the influence of vibration and cavitation. Therefore, the value of K_h is the largest among other types of homogenizers. For example, for the valve homogenizer, high turbulence and cavitation have a significant effect on the dispersion of milk fat, leading to a reduction in K_h to $1100 \times 10^{-6} \text{ m}^{3/2} \cdot \text{s}^{-1}$. For the pulsation homogenizer multiple treatments leads to a reduction in K_h to $225 \times 10^{-6} \text{ m}^{3/2} \cdot \text{s}^{-1}$ (Deynichenko et al., 2018; Samoichuk, 2018; Samoichuk et al., 2019). For the pulsation homogenizer with a vibrating rotor, the influence of resonant phenomena, as well as the developed turbulence and cavitation in the gap between the rotor and the stator leads to a minimum $K_h = 68 \times 10^{-6} \text{ m}^{3/2} \cdot \text{s}^{-1}$ (Samoichuk et al., 2019).

CONCLUSION

Experimental studies of the dispersion of milk fat in SHSCF and the experimental determination of the stream dispersion index allowed us to determine the critical value of the Weber criterion for the disruption of the fat globule of milk in the milk plasma stream, which is 28. The value of the homogenization coefficient has been determined for the disruption of the fat globule under the condition of a single effect on the emulsion, without the influence of vibration and cavitation: $K_h = 3300 \times 10^{-6} \text{ m}^{3/2} \cdot \text{s}^{-1}$.

On the basis of experimental studies of the patterns of dispersion of milk fat in SHSCF, it is established that to obtain an average size of fat globules of $0.8 \mu\text{m}$ it is necessary to provide a velocity of skim milk of $60 - 65 \text{ m} \cdot \text{s}^{-1}$, to use cream, with a fat content of $40 - 45\%$, to ensure the velocity of the flow of cream $20 - 40 \text{ m} \cdot \text{s}^{-1}$ and the diameter of the cream feed channel of $0.9 - 1.0 \text{ mm}$.

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