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Improving the quality of milk dispersion in a counter-jet homogenizer

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ABSTRACT

Homogenization is a necessary process in the production of drinking milk and most dairy products. Specific energy consumption of the most common - valve homogenizers reaches 8 kW·h/t. A promising way to reduce them is the introduction of more effective - counter-jet homogenizers. The purpose of these studies is to increase the efficiency of machines of this type through a fuller use of the kinetic energy of the jets. To achieve this, the design of a ring reflector was developed and experimental studies of its influence on the efficiency of milk fat dispersion in a counter-jet homogenizer were carried out.

Calculations were made to determine the design parameters of the reflector. An installation for experimental research has been developed, in which the required milk pressure is created with the help of compressed carbon dioxide. 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 research the formula for definition of the angle of the reflector top has been analytically received. Experimental studies proved its validity and allowed to determine the optimal value of its diameter. Comparison of the dependence of the degree of homogenization on the excess pressure in a counter-jet homogenization proves an increase in the degree of dispersion by 15-20% when using a reflector. At the same time, specific energy consumption does not increase. Comparison of the distribution curves of milk fat globules by size after counter-jet homogenization and homogenization with a reflector suggests that the average diameter of fat globules of the experimental method decreases from 0.99 to 0.83 µm. This indicates the high quality of the dispersed characteristics of the milk emulsion after processing in a counter-jet homogenizer with a reflector.

Keywords: milk; homogenization; homogenizer; counter-jet homogenizers, reflector, degree of dispersion.

INTRODUCTION

Homogenization is a necessary process in the production of drinking milk and most dairy products. The benefits of homogenized products are undeniable: reducing the sludge of cream and increasing the shelf life of milk, improving the taste and sensory properties of dairy products, increasing the digestion of milk fat and its even distribution throughout the product, etc. **(Dhankhar, 2014)**.

When milk is homogenized, its fat phase is dispersed (fat globules are crushed), as a result of which the average fat particle size decreases from 3–5 to 0.7–1 µm **(Walstra, Wouers and Geurts, 2006)**. This result can be achieved by exposing milk to pressure and velocity via ultrasonic, cavitation, vacuum, and high-frequency electrical treatment **(Nuzhin and Gladushnyak, 2007; Samoichuk et al., 2016)**. Taking into account of such a wide range of effects on the milk emulsion, dozens of types of homogenizers have been developed, which differ significantly from each other both in design and principle of action **(Fialkova, 2006; Dhankhar, 2014)**.

A modern homogenizer must have a high efficiency (degree) of homogenization at low energy consumption. Moreover, the high degree of homogenization is crucial, which is confirmed by the fact that the vast majority of homogenizers of processing plants are valvular. When processing milk in such machines, the average diameter of fat globules reaches the value of 0.75 µm, and the amount of energy consumption per unit of processed product is the highest among all existing homogenizers **(Rayner and Dejmek, 2015)**. Vacuum, ultrasonic, cavitation, mixing, electrohydraulic, screw and spunbond devices for homogenization with significantly lower energy consumption have a lower degree of homogenization **(Fialkova, 2006; Dhankhar, 2014; Nuzhin and Gladushnyak, 2007)**. The degree of homogenization is close to the valve rotor-pulsation and vortex homogenizers. But a product that has been processed in rotary homogenizers has large fat content, which negatively affects the quality of dairy products made from such milk **(Fialkova, 2006).**

High-efficiency jet homogenizers are distinguished, namely: jet with separate supply of fat phases **(Samoichuk et al., 2020)** and counter-jet **(Samoichuk, 2008)**. Such homogenizers, the only ones among the existing ones, provide the highest speed of flow of the fat globule through the flow of milk plasma. After all, the Weber criterion depends on this value, which is a generalizing indicator for the main factors of dispersion of the fat phase of milk **(Samoichuk et al., 2019)**. Weber's destruction coincides with the theories of homogenization by N. Baranovsky, P. Rebinder, and A. Wittig, M. Oreshina, and by Innings's experimental studies **(Oreshina, 2010; Innings and Trägårdh, 2005)**.

Counter-jet homogenizer is not inferior to the valve regaring the degree of dispersion of milk, but has a specific energy consumption of 4-5 times less **(Samoichuk, 2008)**. This indicates a high potential for hydrodynamic dispersion, which is carried out in the collision of jets of milk emulsion.

In the study of such a homogenizer, it was found that the disruption of fat globules of milk mainly occurs in the central part of the zone of collision of jets **(Samoichuk, 2008)**. After that, the jets divaricate fan-shaped (circularly). Their speed, and hence kinetic energy, is quite high. But this energy is not used for dispersion, so it reduces the efficiency of the homogenizer.

It is known that the disruption of fat globules of milk occurs when a jet of milk collides with a hard surface **(Nuzhin and Gladushnyak, 2007; Deynichenko et al., 2018)**. With respect to the counter-jet homogenizer, such a surface may be an annular reflector located in the path of milk flows after the collision.

Scientific hypothesis

The hypothesis of this study is the possibility of increasing the dispersion efficiency of the counter-jet homogenizer by installing an annular reflector.

The aim of this article is to evaluate the effectiveness of dispersing milk in a counter-jet homogenizer with a reflector.

To achieve this aim it is necessary:

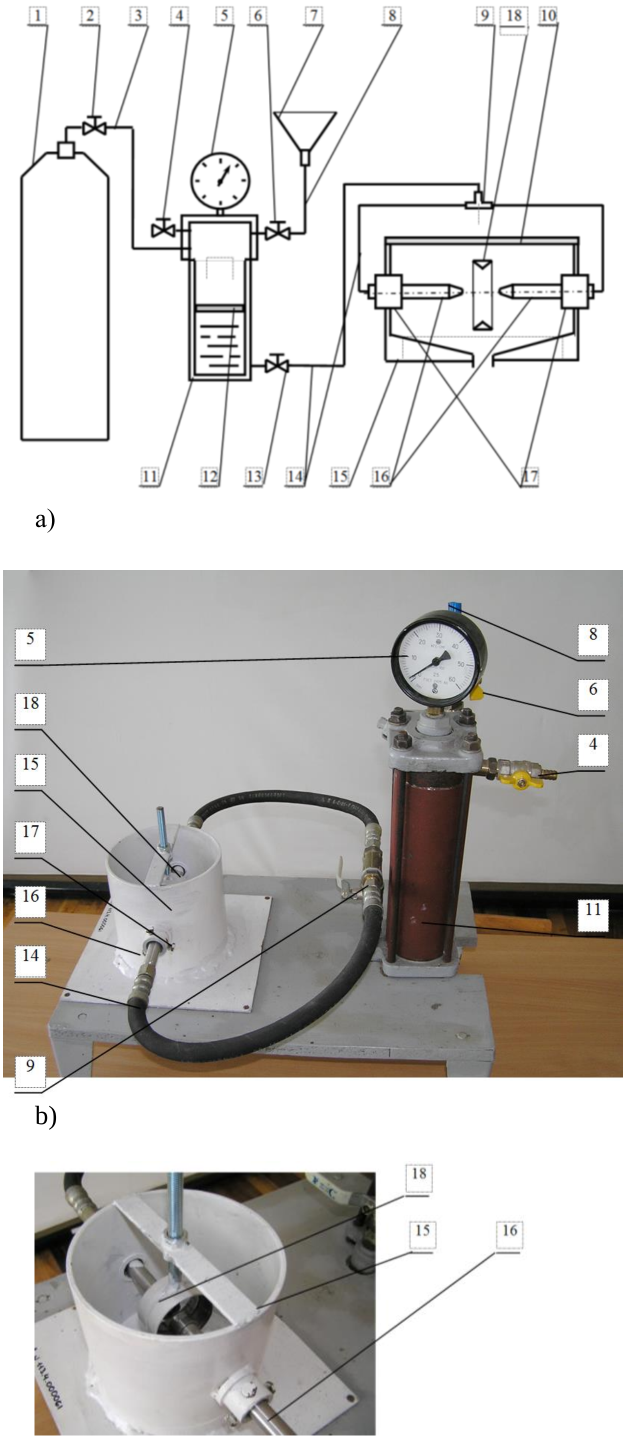
- to develop the design of the annular reflector;
- experimentally determine the effect of the main parameters of the counter-jet homogenizer with a reflector on the degree of homogenization of milk;
- evaluate the dispersed indicators of the milk emulsion after homogenization

MATERIAL AND METHODOLOGY

Experimental equipment

For experimental research, the device was designed, the scheme of which is presented in Figure 1 **(Samoichuk, 2008)**.

The device consists of a chamber 15, in which the nozzles 16 are installed. The bottom of the chamber is made conical with a slope to the center, where the hole for milk removal after homogenization is placed. At the top, the chamber is closed with a transparent lid 10 to allow the process to be monitored. The sleeves 17 for adjusting the position of the nozzles with radially located screws allow changung the distance between the nozzles and achieving their alignment. Nozzles are made collapsible with a possibility of replacement of nozzles.



a)

b)

c)

Figure 1 Scheme a), General view b) and chamber c) of the laboratory device for the study of counter-jet homogenization of milk:

1 – the gas cylinder; 2 – the discharge valve; 3 – the air duct; 4 – the outlet valve; 5 – the manometer; 6 – the filling valve; 7 – the funnel; 8 – the hose; 9 – the tee; 10 – the cover; 11 – the cylinder; 12 – the piston; 13 – the main valve; 14 – the hydraulic hoses; 15 – the camera; 16 – the nozzles; 17 – the bushings for adjusting the position of the nozzles; 18 – the reflector.

Creation of the required pressure of milk is achieved by the gas cylinder 1 and the cylinder 11, which are connected by the air duct 3. The pressure is controlled by the pressure gauge 5. The discharge valve 2 is used to fill the cylinder with gas from the cylinder. The milk is poured into the cylinder by means of the funnel 7 of the hose 8 and the filling valve 6. The outlet valve 4 is necessary for the release of gas from the cylinder when it is filled with milk. The piston 12 prevents the diffusion of gas into the milk and, thus, changing its properties.

The cylinder and the nozzles are connected by hydraulic hoses 14. The division of the main milk flow from the cylinder into two equal flows is carried out in the tee 9. The main valve 13 is used to supply milk under the required pressure to the nozzles.

When performing the tests, the required volume of milk was poured into the cylinder through the funnel, open filling and outlet valves. The main valve was kept closed. To create the necessary pressure in the cylinder the cylinder of carbon dioxide GOST 8050-85 was used. After opening the discharge valve (outlet and filling valves are closed), carbon dioxide was supplied to the cylinder and the pressure in it increased to the required value. The device uses a manometer with a limit value of the measured pressure of 100 kgs / cm^2, accuracy class 0.75 according to GOST 2405-85. When the main valve was opened, the milk under the required pressure was sent to the nozzles, in which jets were formed. After homogenization, the milk was gravitationally discharged through a hole in the lower part of the chamber.

The main factors of the experimental studies were: the excess pressure of the milk supply to the nozzles Δp and the diameter of the nozzles cone d_n. The distance between the nozzles *a* was taken to be equal to half the diameter of the nozzles cone **(Samoichuk, 2008)**. The temperature of milk during homogenization was assumed to be 60–70 degrees **(Walstra, Wouers and Geurts, 2006)**. For counter-jet homogenization, the excess pressure is related to the modified Weber criterion We^{o-s} by the ratio

$$We^{o-s} = \frac{6\rho_p \cdot \varphi^2 \cdot \Delta p}{10^6 \sigma_{f-p} \cdot \rho_m}, \qquad (1)$$

де ρ_p, ρ_m – density of milk plasma and milk, kg/m^3;

φ – hydraulic coefficient of jet speed;

σ_{f-p} – surface tension between milk fat and plasma, N/m;

Δp – excess milk supply pressure, Pa.

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

Statistical analysis

The degree of homogenization of milk was determined by the formula **(Nuzhin and Gladushnyak, 2007; Loncin and Merson, 1979)**

$$Hm = \frac{d_0}{d_k}, \qquad (2)$$

where d_k, d_0 – the average diameter of fat globules after homogenization and before it, µm.

Average diameters of fat globules and other 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 640x480) **(Samoichuk at al., 2020)**. 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 2010 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 2010.

McBrain VA 318 electric wattmeter (Volga region plant of power equipment, Russia) was used to record power.

RESULTS AND DISCUSSION

Rationale for the design of the reflector

For efficient operation of the annular reflector, it is necessary that the liquid flows after their collision with the annular reflector do not intersect with the main jets of milk (coming out of the nozzles). Otherwise, there will be a violation of the continuity of the main jets and a decrease in the degree of dispersion of milk emulsions. To meet these requirements, the annular reflector in radial cross-section must have the shape of an equilateral triangle, the vertex of which faces inwards of the annular reflector. With this design, the jets reflected from the surfaces of the reflector are removed outside the main jets of milk, which is necessary to prevent their crossing (Figure 2).

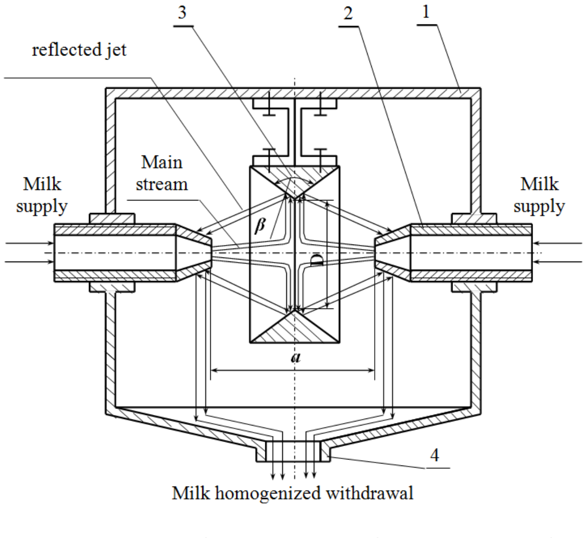


Figure 2 Scheme of the location of the annular reflector and the direction of milk flows in the process of homogenization:
1 – the camera body, 2 – the nozzle, 3 – the annular reflector, 4 – the hole for draining homogenized milk, D -

diameter of the reflector, β - angle of the reflector, *a* – the distance between the nozzles.

To prevent the intersection of the main jets of milk with those reflected from the reflector, it is necessary to calculate the angle β (Figure 3).

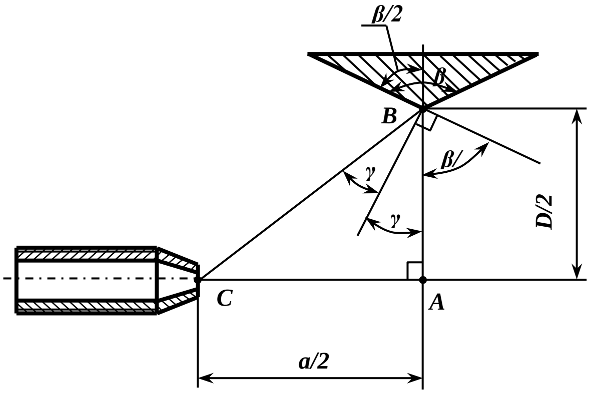


Figure 3 Calculation scheme for determining the angle β of the annular reflector

The jet of milk after the collision will move from point A to B and collide with the annular reflector at an angle γ. The angle of reflection from the surface of the annular reflector will also be equal to γ and the emulsion stream after reflection from the annular reflector will move in the direction from point B to C. That is, perpendicular to the surface of the annular reflector is the bisector of the angle ABC. Therefore, after the necessary transformations, we find that to fulfill the condition of non-intersection of flows of homogenized and non-homogenized products, the angle of the annular reflector must meet the condition

$$\beta = 180^0 - \mathrm{arctg}\frac{a}{D} \qquad (3)$$

The counter-jet homogenizer with a reflector works as follows. Whole milk is fed into the nozzles under the required pressure, which depends on the required degree of homogenization. After passing through the cones of the nozzles, the milk jets meet, while the fat fraction of milk is dispersed and mixed. The coaxial arrangement of the jets allows the fullest use of the kinetic energy of the fluxes for grinding the dispersed phase **(Samoichuk, 2008)**. After collision and homogenization, the product flow diverges fan-like perpendicular to the direction of the jets and hits the annular reflector. This results in final grinding and partial mixing of the dispersed phase of the mixture **(Nuzhin and Gladushnyak, 2007)**. After contact with the annular reflector, the mixture is reflected from it and enters the housing of the device for homogenization, where it is gravitationally removed from the machine. Moreover, due to the properly calculated angle of the annular reflector β, the product streams after contact with the annular reflector are reflected outside the jets coming out of the nozzles, resulting in no intersection of the flows of non-homogenized and homogenized products. Thus, in the counter-jet homogenizer with a reflector, the dispersion of the fat phase of milk occurs in 2 stages: when the jets collide with each other and when the secondary jets collide with the reflector. This allows you to more fully use the energy of the flow of milk.

The results of experimental studies

To determine the effect of excess pressure and the angle of the reflector on the degree of homogenization, an experiment was performed, the results of which are shown in Figure 4.

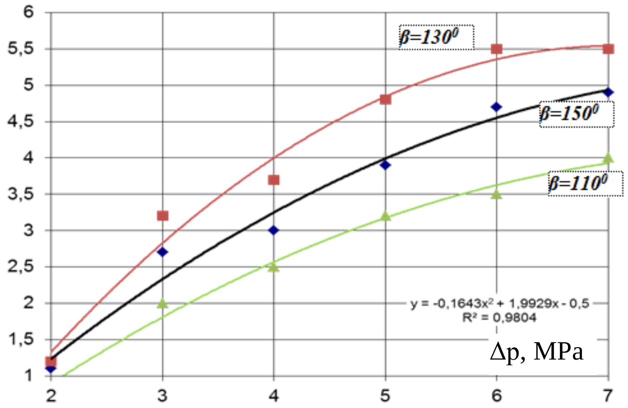


Figure 4 Dependence of the influence of excess pressure and the angle of the reflector on the degree of homogenization at a temperature of 70^0C.

With increasing excess pressure, the degree of homogenization increases by parabolic dependence. At higher values of excess pressure, the growth of the response function (Hm) slows down. The prediction performed by the computer program Microsoft Office Excel 2010 **(Lawrence, Ronald and Sheila, 2009)** shows the maximum achievable degree of homogenization of 5.6 at an overpressure value of 7.4–7.5 MPa.

The optimal value of the angle of the reflector, calculated by formula (3) is 130^0. This achieves the highest degree of dispersion of the fat phase of milk – milk flow after reflection from the surfaces of the reflector is directed to the nozzle body and does not interfere with free exit of the main jet from the nozzles. At an angle of the reflector β = 150 degrees, the flow of milk strikes further on the body of the nozzles. In this case, due to the greater distance, the jet speed becomes smaller, so the efficiency of additional homogenization decreases. At an angle of the reflector β = 110^0, the milk flow after the reflector intersects with the jets coming out of the nozzles, so the continuity of the milk flow is disturbed, its normal velocity component falls, so the decrease in the degree of homogenization is more significant.

The existence of the maximum degree of dispersion of milk fat indicates the identity of the mechanisms of homogenization during pushing through a narrow slit and in the studied process **(Håkansson et al., 2010; Håkansson et al., 2013; Rovinsky, 1994; Deynichenko, 2018; Yong, Islam and Hasan, 2017)**. Let us compare the experimental curve of the dependence of the degree of homogenization on the excess pressure with the theoretical one φ=0.984, a=0.5 mm, dc=1.0 mm, T=65^0 C (Figure 5).

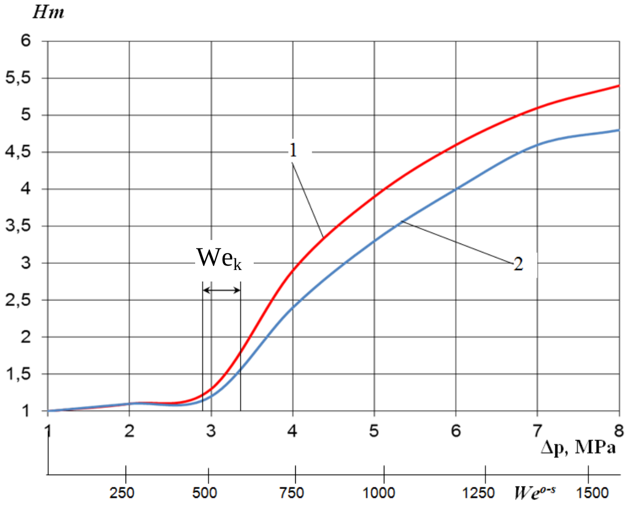


Figure 5 Comparison of the dependence of the degree of homogenization on excess pressure and the modified Weber criterion (at T=70 degrees, a=0,56 mm, d_c= 1 mm): 1 – the counter-jet homogenizer with a reflector; 2 – the counter-jet homogenizer without a reflector.

The deviation of the values of the experimental curve of the modernized homogenizer in comparison to the homogenizer without a reflector is 15-20%. Indeed, the increase in the degree of homogenization during the installation of the reflector is due to a more complete use of the kinetic energy of the milk flow in additional contact with the reflector and the nozzle housing.

Approximating the data of Figures 5 with a straight line, we obtain an expression that is identical in content to the known dispersion formula **(Loncin and Merson, 1979)**

$$\mathrm{Hm} = 0.9 \cdot 10^{-6} \Delta \mathrm{p} \cdot \varphi^2 . \qquad (4)$$

The coefficient of determination (R^2) in the range of 2.5 <Hm <6.0 is 95%, and at Δp = 5.0–6.0 MPa and the degree of homogenization 4.5–5.2 the difference between theoretical and practical data is minimal. At Δp = 6.5 MPa, this difference reaches 6% and with a further increase in excess pressure, it is possible to predict its rapid increase. In the range Δp = 2–3 MPa there is an intensive increase in the degree of grinding of the fat phase of milk. Here the deviation of experimental data from the specified (approximated) dependence is maximal. At the value of Δp <2 MPa homogenization practically does not occur.

The critical value of the Weber criterion (the beginning of the grinding of the fat phase) corresponds to the range of values of excess pressure of 1.8–2.2 MPa, at which We = 500–600.

Therefore, the optimal parameters of counter-jet homogenization for dc = 1 mm are: a = 0.5 mm, T = 60–65^{0}C. The value of excess pressure depends on the required degree of homogenization and is Δp = 6.5 MPa at Hm = 5.0.

The results of experimental determination of the degree of homogenization and Weber criterion, with cones diameters of nozzles 1.0; 1.5 and 2.0 mm, depending on the distance between the nozzles cones are shown in Figure 6. The diameter of the cone does not affect the maximum degree of homogenization.

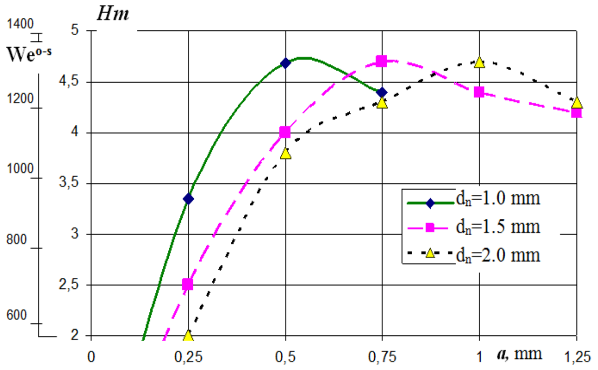


Figure 6 Dependence of the degree of homogenization and the modified Weber criterion on the distance between the nozzles cones

It should be noted that at $a < d_c / 2$ the degree of homogenization is higher by 15–40% than theoretically calculated **(Samoichuk, 2008)**, and the velocity of the jets at $a < d_c / 2$ corresponds to the calculated data. This can be explained by a more sudden change in the velocity of the fat globule after the collision of jets (which leads to an increase in the velocity difference between the fat globule and the surrounding plasma), due to the strict limitation of boundaries of the jet flow that is diverted by the edges of the nozzles **(Samoichuk and Kovalyov, 2013)**. Therefore, the optimal location of the nozzles is at a distance equal to half the diameter of the nozzle cone **(Samoichuk, 2008)**.

To determine the diameter of the annular reflector of the counter-jet homogenizer the experimental study was conducted with reflector diameters D = 40, 50 and 60 mm. The results are shown in Figure 7.

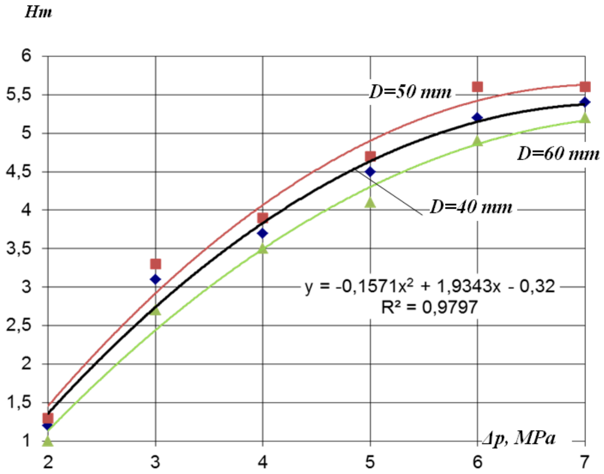


Figure 7 The results of experimental determination of the degree of homogenization depending on the pressure and diameter of the reflector.

It is optimal to use a reflector with a diameter of 50 mm as we obtain the maximum degree of fat dispersion. At D = 40 mm, the degree of homogenization decreases by 0.2–0.3, that is by 5%. This can be explained as follows. When using a reflector with a smaller diameter to comply with formula (3), the angle β decreases and the impact on the reflector becomes more sliding, which reduces the degree of homogenization. At D = 40 mm, the degree of homogenization decreases by 0.5–0.6, ie by 10%. This is due to the increase in loss of flow velocity before the collision with the reflector.

Changes in the fractional composition of fat globules after counter-jet homogenization (at T = 65^{0}C, Δp = 3.5 MPa) and comparing them with homogenization with a reflector (at a pressure of 4 MPa and T = 65^{0}C) and whole milk **(Nuzhin and Gladushnyak, 2007 ; Dhankhar, 2014)** are graphically represented in Figure 8, and micrographs of fat globules are in Figure 9.

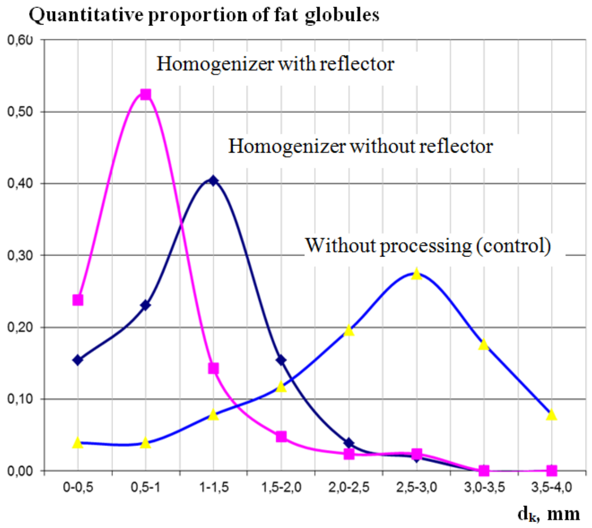
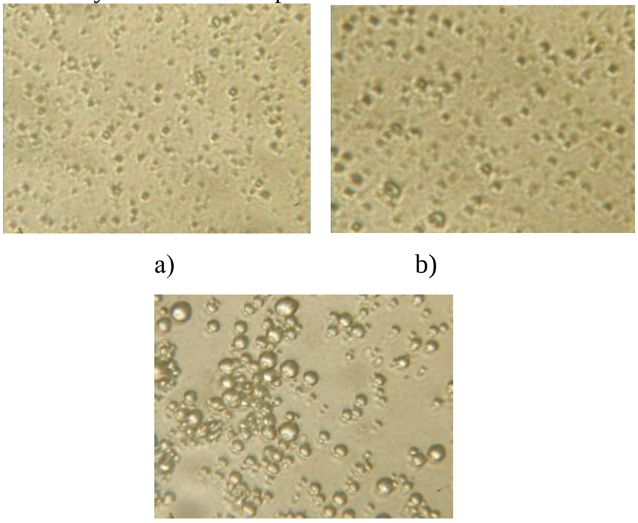


Figure 8 Differential distributions of fat globules of milk

Milk before homogenization is characterized by the following parameters: average diameter of fat globules dk = 2.49 mm, dispersion σ = 1.66, coefficient of variation (the share of scattering of the trait relative to the average) V = 67%. Respectively for milk after counter-jet and countercurrent-jet homogenization with a reflector: dk = 0.99 mm and 0.83 mm, σ = 0.51 and 0.47, V = 51 and 56%.

The value of the coefficients of variation indicates the reliability of the data sample.



a) b)

c)

Figure 9 Photomicrographs of milk samples (400 times magnification):
a) after counter-jet homogenization with a reflector at Δp = 4.0 MPa
b) after counter-jet homogenization at Δp = 4,0 MPa
c) raw milk.

The average diameter of the fat globules with the counter-jet homogenization treatment with the reflector decreased by 19% (from 0.99 to 0.83 µm) compared to the non-upgraded homogenizer. The value of the dispersion also decreased, which indicates the advantage of the counter-jet homogenization with a reflector.

CONCLUSION

The design of the annular reflector has been developed to ensure the condition of free flow after the collision with the surface of the reflector. The reliability of the theoretically obtained dependences for determining the angle of the reflector has been confirmed. It is proved that it's optimal to use the reflector diameter of about 50 mm.

When using a counter-jet homogenizer, it is possible to achieve a degree of homogenization of 5.6 at a value of excess pressure of 7.4–7.5 MPa. The degree of homogenization when installing an annular reflector increases by 15-20%. Moreover, such an increase in quality is provided without increasing energy consumption.

Comparing the data on the distribution of fat globules of milk by size after counter-jet homogenization and homogenization with a reflector suggests that the average diameter of fat globules of the experimental method is 19% smaller. The width of the particle size distribution is also smaller, which indicates better homogenization when installing the reflector.

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