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Energy Efficiency Optimization of Milk Homogenizers: A Contribution to the European Green Deal Goals

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Abstract. The modern global milk processing industry involves the use of innovations and optimization of existing industry management methods, which contributes to the realization of sustainable development and energy efficiency. Increasing the energy efficiency of dispersing and homogenizing milk and dairy products can contribute to the practical implementation of the philosophy of the "European Green Deal". The jet-slot milk homogenizer is one of the most energy-efficient among all types of homogenizers in the dairy industry. The principle of its operation is based on the creation of a maximum speed difference between the fat balls of cream and the flow of skimmed milk. This makes it possible to obtain a high degree of dispersion with high energy efficiency of the process. Reducing the specific energy consumption and finding the optimal parameters of the homogenizer were based on the results of both theoretical and experimental studies and were carried out graphically. The optimization criteria (decreasing specific energy consumption while maintaining high homogenization quality) were chosen to achieve a dispersion of 0.8 μm with minimal energy consumption. The diameter of the confusor is optimized at the point of greatest narrowing. The obtained results indicate that to increase the energy efficiency of homogenization, the parameter values should be within 3.5–4.0 mm. The parameters of the width of the ring gap, the fat content and the speed of the cream are optimized. The results showed that it is possible to reduce the specific energy intensity of the process to values of 0.88–0.92 kWh/t when using cream with a fat content of 33–43%, which should be fed through an annular gap with a width of 0.6–0.8 mm. Optimum values of the cream feed speed were found, which should be equal to 7–11 m/s. The research results are of high practical value for the further development of an energy-efficient industrial model of a jet-slot homogenizer.

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1. Introduction

The integration of Ukraine into the European space, where the "European Green Deal" agreement was signed, provides for the creation of a resource-efficient and competitive economy in the member states of the Union (European Green Deal, 2019). Among the declared priority directions of the program, priority attention is paid to increasing the energy efficiency of various types of equipment, in particular, within the framework of the "From farm to fork" strategy (Delivering the European Green Deal, 2019). Therefore, the further development of technologies in the field of food processing should be aimed at the research and implementation of energy-efficient types of equipment, one of which is the developed homogenizer Labenko, et. al (Labenko, 2022). Due to the very high energy consumption of homogenization processes in drinking milk and drinking cream production lines, up to 50-60% of energy consumption is spent only on the work of the homogenizer. Therefore, a significant reduction of energy costs for homogenization will lead to a reduction of energy costs for the production of milk and cream by up to 50% (Fialkova, 2006; Labenko, 2022). For the European market, this amounts to more than 1 billion US dollars in annual savings.

From the point of view of ensuring the high quality of dairy products, most of their production technologies include the operation of dispersing the dispersed phase of milk emulsion (DPME) (homogenization). Whole milk is an unstable emulsion and, in the absence of extraneous mechanical or thermal influences, separates into the DPME and skimmed milk after a short period of time. This phenomenon is explained by the high values of the average diameter of milk fat droplets (ADMFD), which in raw milk is about 3-4 μm. In turn, the delamination of the milk emulsion causes the deterioration of the quality of dairy products. This phenomenon manifests itself in an increase in the loss of DPME on the walls of equipment and containers, a decrease in the shelf life, and a decrease in the nutritional and energy value of products Fialkova (Fialkova, 2006). In order to prevent the occurrence of the above negative consequences, in accordance with the production technologies of almost all dairy products, homogenization is provided as a standard operation.

Homogenization involves reduction of the ADMFD of dairy products by 3–5 times, ensuring uniform distribution of DPME by volume and resistance of products to delamination during storage. According to Dhankhar (Dhankhar, 2014), to ensure the compliance of dairy products with the standard of regulatory documentation, their ADMFD should be not more than 0.75–0.85 μm (on average, 0.8 μm). These standards are met by the valve-type dispersers most common in the industry. After processing in them, the ADMFD of dairy products does not exceed 0.80 μm. At the same time, the use of these constructions for dispersing cuts off excessively high values of specific electricity consumption, exceeding 7 kWh/t of processed milk (Dhankhar, 2014). According to this indicator, valve dispersers approach the energy consumption of the grain grinding process (7–16 kWh/t). It should be noted that the percentage of homogenization in the balance of total energy consumption of dairy products processing is up to 40%, depending on the technology (Bulgakov et al., 2019a; Cai, 2017). Therefore, the purpose of the research is to increase the energy efficiency of the jet-slot homogenizer of milk, which is achieved by studying the optimal values of the structural, technological, and hydraulic parameters of the suggested homogenizer. Thus, reducing energy cost of dispersing the DPME is an urgent and priority task for milk processing enterprises and industry researchers. The scientific contribution of the conducted research consists in the development of the scientific foundations of dispersing dairy products. The practical significance of the research lies in finding the optimal values of the parameters of the suggested homogenizer, which will ensure an increase in the energy efficiency of the homogenizer, and therefore the competitiveness of the products.

2. Literature review

Developing the newest designs which allow solving the problem of high energy consumption of homogenization is connected to the characteristic difficulties of its research. Thus, visual observation of the deformation and destruction of the dispersed phase emulsion is a difficult task from a technical point of view. This is due to the low transparency of the investigated liquids, the microscopic size of the fat droplets, and the high speeds of the liquid movement (over 100 m/s). The complex effect of these factors caused the absence of a general theory of homogenization. As a result, about 8–10 hypotheses of the dispersion of the DPME were put forward (Huppertz, 2011; Innings, 2005). Each of them has contradictions and does not comprehensively explain the essence of the processes that take place in the area of the valve gap when using the most common valve disperser in the milk processing industry. Designs of dispersers, which were created on the basis of these hypotheses, either do not provide the necessary reduction of ADMFD to 0.8 μm (vacuum, vibration, rotary-pulsation, electrohydraulic), or have high values of specific energy consumption (SEC) (valves, microfluidizers) (Dhankhar, 2014; Tartar, 2009).

The scientific basis for the development of new designs of energy-efficient dispersers can be the identification of the Weber criterion as the main factor of dispersion. Milk as a polydisperse system consists of dispersive (skimmed milk) and dispersed (cream) phases. It is possible to achieve a value of Weber's hydrodynamic criterion sufficient for the effective destruction of fat droplets by creating a high difference in phase velocities (the speed of the flow of milk plasma around the fat droplet). The advantages of this approach include the possibility of developing predictably energy-efficient structures (Dhankhar, 2014; Samoichuk et al., 2019a). The introduction of dispersers, the principle of operation of which is based on the implementation of this principle, allows reducing the energy costs of dispersion by 50–60% (Ciron, 2010; Samoichuk et al. 2020a; Samoichuk et al., 2019a). Various types of jet milk dispersers meet the listed standard. According to researchers (Samoichuk et al. 2020a; Samoichuk et al., 2019a), their use ensures a reduction of ADMFD to 0.75 μm. The SEC of such designs is 0.90–1.80 kWh/t. Therefore, further research of this particular group of dispersers is predicted to be able to reduce energy cost of dispersion during the processing of various dairy products.

In order to reduce energy, cost of dispersion, researchers proposed and investigated devices (Dhankhar, 2014; Håkansson, 2013):

- cavitation;
- impact-jet;
- mini-mixers with different profile shapes of internal surfaces;
- dispersant in volume;
- microfluidizer;
- jet disperser of milk with counter supply of cream;
- opposite-flow jet;
- jet milk disperser with separate DPME supply.

We will analyze them (Fialkova, 2006; Tartar, 2009).

The use of microfluidizers makes it possible to obtain a product with the highest dispersion of the fat content of milk emulsion (ADMFD does not exceed 0.10 μm) (Capretto, 2011; Erbil, 2012). However, despite the provision of ADMFD at the level of the standard of regulatory documentation, their productivity is less than 500 l/h, which does not meet the needs of the dairy industry (Vladisavljevic, 2017; Yong, 2017). In addition, microfluidizers have specific energy costs that exceed the corresponding indicators for energy-intensive valve dispersers (Wang, 2020; Ward, 2015). The set of the above features determined the narrow scope of use of these designs, mostly in the chemical and pharmaceutical industries (Lee, 2011; Valencia-Flores, 2013).

Studies (Dhankhar, 2014; Erbil, 2012) predicted that the introduction of a cavitation disperser can ensure high reduction of energy cost of dispersing the DPME emulsion. The principle of its operation is based on the corresponding hypothesis Dhankhar (Dhankhar, 2014) and consists in the occurrence of cavitation during the oscillation of the plates, or active working bodies that interact with milk emulsions. The test results proved that the use of dispersants of this type provides a reduction in SEC to 1.1–1.3 kWh/t Tartar (Tartar, 2009). At the same time, dairy products processed in cavitation-type dispersers have ADMFD of about 1.00–1.20 μm (Fialkova, 2006), which does not meet modern standard. Further studies outlined in Innings, et. al (Innings, 2005) allowed us to find out the secondary role of the cavitation process among the factors causing the destruction of fat droplets.

Our group of researchers (Acharyaa, 2021; Cai, 2017), based on classical theories of homogenization, made an attempt to reduce energy cost of dispersion due to the development and research of Y-shaped, T-shaped, U-shaped and rhombic-shaped mini mixers. The principle of their operation consists in supplying the necessary amount of skimmed milk through the channels, to which a certain amount of DPME is supplied in the direction perpendicular to the movement of the dispersion phase (Fonte, 2020; Minakov, 2012). When they are used, a decrease in ADMFD in dairy products is ensured to 1.10–1.30 μm (Cao, 2017; Dhankhar, 2014), which is also higher than the indicators determined by the standard of regulatory documentation. The use of the principle of separate supply of skimmed milk and DPME in them has been predicted to reduce the SEC of dispersion to 1.3–1.7 kWh/t (Roudgar, 2012; Tartar, 2009).

However, further studies revealed the impossibility of reducing energy cost of these designs due to the implementation of structural and technological improvements (Di Marzo, 2016; Malkina, 2022; Thomas, 2010). This is explained by the fact that in order to ensure the reduction of ADMFD to the level of the standard of regulatory documentation, it is necessary to increase the speed of liquid movement (to achieve the hydrodynamic conditions necessary for effective dispersion) (Dreher, 2009; Foroughi, 2011; Yagodnitsyna, 2016). A natural consequence of this will be an increase in the energy consumption of homogenization. Some researchers (Camarri, 2022; Lobasov et al., 2018a) considered it possible to reduce energy cost by optimizing the internal profile of the working surfaces of mini-mixers. However, the results of the conducted research show that changing the shape of the profile of the internal surfaces of the devices is not able to provide a significant increase in the speed of movement of skimmed milk without increasing the energy consumption of the process (Darekar, 2017; Fani, 2013). Mini-mixers developed in this way are not able to create the necessary speed difference between the dispersed and continuous phases of the emulsion, which is a necessary condition for reducing energy cost of homogenization (Hussong, 2009; Lobasov et al., 2018a; Yermakov, 2021).

It is predicted that the shortcomings of mini-mixers can be eliminated by the use of a countercurrent-jet milk disperser (Samoichuk et al., 2019a; Tartar, 2009). The homogenization of the milk emulsion in it occurs due to the creation of conditions under which the difference between the speeds of milk plasma and DPME is of significant importance. During the operation of this device, dispersion occurs as a result of the collision of two jets of milk in the air Samoichuk, et. al (Samoichuk et al., 2019a). Effective dispersion during the processing of dairy products in a disperser of this type is manifested in the reduction of ADMFD after processing to 0.75 μm. total energy consumption when using such a design is 1.6–1.8 kWh/t (Samoichuk et al., 2019a). A characteristic shortcoming of the counter-current milk disperser is foaming, which is explained by the destabilization of the protein phase of milk during dispersion in an air environment (Fialkova, 2006). The impact-jet disperser has similar indicators of energy consumption, ADMFD after dispersion, and disadvantages Haponiuk, et. al (Haponiuk, 2015).

Research conducted in (Samoichuk et al. 2020a; Samoichuk et al., 2019a) shows the results of using the principle of separate feeding of skimmed milk and cream. One of such designs is little-studied jet milk disperser with a counter feed of cream. After preliminary separation, a thin stream of the DPME is fed through the tube in the opposite direction to the movement of the high-speed flow of skim milk Dejnychenko, et. al (Dejnychenko, 2016). The use of such a design involves the occurrence of a cumulative effect, which will be observed when the jet and the flow collide, which ensures a reduction of the ADMFD to 0.75 μm (Dejnychenko, 2016; Dhankhar, 2014). At the same time, the course of the process below the liquid level allows avoiding the phenomenon of foaming. Nevertheless, according to the results of analytical studies, the SEC of such a device is 1.3–1.5 kWh/t (Dejnychenko, 2016; Samoichuk et al.. 2020a). Relatively high values of electricity consumption of this design are explained by additional energy consumption. They are associated with the need to create additional pressure that prevents the tube from being pushed out of the homogenization chamber.

The results of the latest research indicate that it is possible to ensure reducing energy cost of dispersion when introducing a jet disperser of milk with a separate supply of dispersed phase (JDMSSDP). In it, after preliminary separation, skimmed milk flows at high speed to the place of the greatest narrowing of the homogenization chamber. In this zone, where the dispersion phase has the highest speed, DPME is fed to it in the required ratio through channels of small diameter (Samoichuk et al., 2019a). The predicted increase in the value of Weber's criterion allows for the reduction of ADMFD during processing in the JDMSSDP to 0.80–0.90 μm (Dejnychenko, 2016; Samoichuk et al., 2019a). Implementation of the principle of separate supply of DPME made it possible to significantly reduce the SEC of dispersion, which is about 0.85–0.90 kWh/t (Dejnychenko, 2016; Rayner, 2015). The disadvantages of this design include the use of channels of small diameter (0.6–0.9 mm), which is a necessary condition for effective dispersion. However, such values of the diameter of the DPME supply channels lead to a decrease in the reliability of the design due to an increase in the rate of obliteration of the internal surfaces of the channels (Liao, 2009; Morales, 2016).

Comparative characteristics with valve and other considered types of dispersers are given below (Table 1 (Appendix A)) (Dejnychenko, 2016; Hussain, 2017).

The results of the analysis of the data in Table 1 indicate that a jet disperser with a counter feed of DPME and JDMSSDP can be used to increase energy efficiency. However, among the characteristic features of these designs there are specific defects, in particular (Dejnychenko, 2016; Deynichenko, 2018; Mohammadi, 2014):

– increasing the energy consumption of dispersion in a jet disperser with a counter supply of cream, due to increasing the pressure to prevent the Pitot tube from being pushed out;

– channels of small diameter, which accelerates obliteration and reduces the reliability of the design.

In order to eliminate the listed defects and in order to reduce energy cost of dispersion, the parameters of the jet-slot type disperser of milk (JSTDM) have been developed and studied. The developed design allows for the implementation of the principle of separate feeding of cream, which leads to an increase in the efficiency of the destruction of fat droplets due to an increase in the value of Weber's hydrodynamic criterion. At the same time, the design features of the developed device allow combining the simultaneous normalization of products by fat content with homogenization. Among the advantages of the JSTDM, the following should be highlighted:

– reduction of SEC while simultaneously ensuring productivity at the level of industrial samples, which is ensured by changing the area of the ring-shaped gap (at the same time, increasing the reliability of the design is ensured by using elastic elements in the structure of the ring-shaped gap, which allows changing its area according to the degree of obliteration of the internal surfaces);

– ensuring the reduction of ADMFD to the level of the standard of regulatory documentation due to the use of a ring-shaped gap of small diameter, which allows to ensure the uniform effect of the flow of skimmed milk on the central and peripheral parts of the DPME jet.

The results of analytical studies of JSTDM confirmed by experimental studies indicate the possibility of obtaining a product whose ADMFD is 0.75–0.85 μm (Deynichenko, 2018; Samoichuk et al. 2020a). At the same time, the energy costs of dispersion are 0.70–0.80 kWh/t (Havrylenko, 2021; Samoichuk et al. 2020c). Further studies of the JSTDM should be aimed at optimizing such parameters as the diameter of the confusor at the zone of the largest narrowing, the width of the ring-shaped gap, the fat content and the speed of the DPME supply. The study of the optimal values of these parameters will allow obtaining the necessary data for the development of the methodology for the calculation of the industrial model and the practical implementation of the industrial model of JSTDM at milk processing enterprises.

The research purpose is to reduce the SEC of JSTDM while obtaining a high quality of homogenization and finding the optimal hydraulic, structural, and technological parameters of the disperser. The obtained data will make it possible to develop a methodology for calculating parameters and to suggest a constructive solution of an industrial energy efficient model of JSTDM for its further implementation at enterprises of the milk processing industry.

To achieve the goal, the following tasks have been set:

– to determine the optimal values of the diameter of the JSTDM confusor in the zone of the largest narrowing;

– to optimize the fat content of the DPME and the width of the ring-shaped gap, which are used to obtain a normalized homogeneous milk emulsion;

– to determine the optimal values of the DPME feeding speed, based on the conditions for ensuring the normative quality indicators while simultaneously reducing the SEC of dispersion.

3. Experimental

The component parts of the laboratory sample of the JSTDM are shown in the block diagram (Fig. 1. (Appendix B)).

The developed device (Fig. 1) consists of a container with skimmed milk after separation, from where it enters the pump. The DPME is fed to the homogenization chamber by a separate pump. In it, a thin ring-shaped flow of DPME is injected into a high-speed flow of skimmed milk (Samoichuk et al. 2020a; Samoichuk et al.. 2020c). The change in the ratio of the supply of DPME in relation to the amount of skimmed milk determines the necessary value of the normalization of the finished milk by fat content.

The design of the JSTDM homogenization chamber is shown in Fig. 2 (Appendix C) (Deynichenko, 2018).

The JSTDM homogenization chamber (Fig. 2) consists of a body part 4 into which profiled inserts 3 and 5 are installed, which represent a baffle and a diffuser, respectively. During the operation of the disperser, skimmed milk will flow through the skimmed milk supply pipe 1 at high speed to the place of the largest narrowing of the confusor. The necessary hydrodynamic conditions for dispersion are created in the space between the zone of the greatest narrowing of the confusor and the initial section of the entrance to the diffuser Samoichuk, et. al (Samoichuk et al. 2020a). In this zone their internal surfaces form a ring-shaped gap (Samoichuk et al. 2020c). The homogenized and fat-normalized milk emulsion is discharged through the tube 6.

The creation of the JSTDM installation (Fig. 3 (Appendix D)) and subsequent experimental research took place on the basis of the Department of Equipment for Processing and Food Production named after Professor F. Yu. Yalpachik of the Dmytro Motornyi Tavria State Agrotechnological University (Ukraine).

The design of the JSTDM provides for the adjustment of the width of the ring-shaped gap from 0 to 1.0 mm, which is achieved by installing or removing additional elements. In this zone, DPME is supplied to the skimmed milk with the help of a rotary type pump 7 from the container 3 through a flexible hose 10. The DPME supply pump is driven from the power source 16 when the toggle switch 15 is started. The amount of DPME entering the homogenization chamber is regulated by potentiometer 13, which controls the rotation frequency of the DPME supply pump drive (Samoichuk et al. 2020a; Samoichuk et al.. 2020c). The homogenized and fat-normalized milk are led to the storage tank by means of a flexible pipeline 14.

The parameters of milk used in the experimental study of the parameters of JSTDM met the standard of ISO 9622: 2013 (Milk and liquid milk products) (ISO 9622:2013). The selection of samples for conducting experiments required compliance with the standard of the ISO 707: 2013 standard (Milk and milk products. Guidance on sampling) (ISO 707:2013).

The size distribution of fat globules after dispersion had been determined using an optical microscope XS-3330 LED (Ukraine) with a digital camera. In order to visualize the fractional distribution of ADMFD on the monitor screen and carry out further processing of the obtained microphotographs, a digital camera MDC-500 (Taiwan) with a graphic resolution of 5 MPix had been used, which was connected to the microscope (Samoichuk et al.. 2020a). As a system that provided calibration of the visualization system and provided a reference system for measuring SLC, an object micrometer of passing light OM-P (Russian Federation) with a division value of 0.001 mm was used. Experiments during testing at different levels of variation of variable process factors had been performed in triplicate. Compliance of the dispersion of milk with the quality standard specified in the regulatory documentation had been determined by the ADMFD size of the milk emulsion of 0.8 μm (Samoichuk et al. 2020a).

The list of other equipment used in experimental research (names, brands, and degree of accuracy) is provided in articles (Deynichenko, 2018; Samoichuk et al., 2019a; Samoichuk et al. 2020c). Constant factors of the dispersion process in JSTDM were the temperature of the cream, the recommended parameters of which were maintained in the range of 35–40°C (Ivanovs, 2020; Jiang, 2019) and the temperature of skimmed milk 60–65°C (Bulgakov et al., 2019a; Bulgakov et al., 2019b; Gossett, 2010). The variable factors of the research were: productivity, the width of the ring-shaped gap, excess pressure of the supply of skimmed milk, fat content and the speed of the supply of the DPME (Hulevskyi, 2019).

When conducting experimental studies, the range of variation of variable factors is substantiated in detail in articles (Postelmans, 2020; Samoichuk, 2023; Samojchuk et al., 2019b) and was:

– excess pressure of the supply of skimmed milk (1–3 MPa);
– the width of the ring-shaped gap (0.1–0.9 mm);
– speed of cream (5–110 m/s);
– disperser productivity (400–1600 l/h);
– fat content of cream (10–50%).

The process of dispersing milk in JDMSSDP should ensure the reduction of the average size of fat droplets to the level of 0.80 μm with minimal energy costs. Thus, the hydraulic, structural and technological parameters of the disperser, which meet these standards, were considered optimal.

Optimal parameters were determined graphically. For this, lines of equal dispersion (0.8 μm) were constructed on the graphs of dependences of the SEC at different values of the rational values of the selected factors (fatness of the cream F_c, width of the ring-shaped gap h, speed of the cream υ_c, narrowing diameter of the disperser chamber. After that, the values of the factors had been found, in which the SEC is minimal. To determine the optimal parameters of the milk homogenizer, it is necessary to construct lines of equal dispersion on the graphs of the dependences of the specific energy consumption E_s at different productivity Q_s (Fig. 4) and different values of the rational values of the diameter of the confusor at the place of the greatest narrowing, determined during analytical studies of the jet-slot homogenizer . After that, according to the data determined from the experimental graphs at the level necessary to ensure the average diameter of the fat globules at the level of the requirements of the regulatory documentation, a line of equal dispersion (0.8μm) is drawn, indicated on the graph with a solid line. At the intersection of the line of equal dispersion, which has a value of 0.8 μm, with each of the curves in the legend, we find the corresponding values of the specific energy consumption. We plot the found values of the specific energy consumption on the previously constructed graphs of the dependence of the specific energy consumption of the homogenizer on the productivity of the homogenizer at different values of the confusor diameter at the place of the greatest narrowing and look for the minimum values on the obtained graph, which will be the optimal values of the d_c parameter.

4. Results and discussion

Analytical dependences of the JSTDM parameters made it possible to obtain the dependence (1). It links technological, structural, and hydraulic parameters, in particular, the Weber failure criterion, ADMFD, productivity, jet-slot homogenization coefficient, and the diameter of the confusor at the zone of greatest narrowing.

$$d_a = \frac{We_k \cdot \sigma_{f-p} \cdot {\varepsilon_c}^2 \cdot \pi^2 \cdot d_c^4}{32 \cdot \rho_p \cdot {k_s}^2 \cdot Q_s^2}, \quad (1)$$

where We_k – the critical value of Weber's criterion;

$\sigma_{f\text{-}p}$ – surface tension at the phase interface, N/m;

k_s – coefficient of crevice homogenization with transverse feeding of cream, which takes into account the influence of fat content, speed and width of the ring-shaped gap for feeding cream;

ρ_p – density of milk plasma, kg/m^3;

d_c – the diameter of the confusor at the zone of greatest narrowing, mm;

Q_s – productivity of the jet-slot disperser for skimmed milk, kg/h;

ε_c – the compression coefficient, which takes into account the hydrodynamic conditions in the area where the DPME enters the flow of skimmed milk.

The analysis of the obtained dependence (1) shows that in order to increase the dispersion of the DPME during homogenization of milk in JSTDM (reduction of d_a), it is necessary to fulfill conditions (2) Deynichenko, et. al (Deynichenko, 2018).

$$\begin{gathered}(We_k,\ \sigma_{f-p},\ \varepsilon_c,\ d_c) \to min; \\ (k_s,\ Q_s) \to max,\end{gathered} \quad (2)$$

It is possible to reduce the surface tension at the fat-plasma interface by increasing the dispersion temperature and by using emulsifiers. It is possible to increase the value of the coefficient of jet-slot homogenization by optimizing the width of the slot in the place of the greatest narrowing, the fat content in the DPME and the flow rate of the DPME (Postelmans, 2020; Samoichuk et al., 2019a). These problems had been solved in the course of experimental studies with subsequent optimization of the parameters of the JSTDM.

Further analytical studies made it possible to obtain the dependence of the SEC of dispersion in the JSTDM on the main parameters of the developed device (3) (Deynichenko, 2018; Samoichuk, 2023)

$$E_s = \frac{{Q_s}^2 \left(\frac{8 \cdot \rho_p}{\mu_c^2 \cdot d_c^4} + \left(\frac{F_n - F_s}{F_c - F_n} \right)^3 \cdot \frac{\rho_c}{2 \cdot d_c^2 \cdot h^2 \cdot \mu_s^2} \right)}{\pi^2 \cdot \rho_m \cdot \left(\frac{F_c - F_s}{F_c - F_n} \right)} \quad (3)$$

where ρ_m – milk plasma density, kg/m^3;

ρ_c – density of cream, kg/m^3;

h – width of the ring-shaped gap, mm;

F_s, F_c, F_n – fat content of skimmed milk, cream and normalized emulsion, respectively, %;

μ_c, μ_s – flow coefficients of the confusor and ring-shaped gap, respectively, which take into account the hydrodynamic conditions in the area where the cream enters the skimmed milk flow.

The analysis of the obtained dependence (3), which links the specific energy costs of dispersion, structural, hydraulic and technological parameters of the developed JSTDM shows that a reduction in the specific energy costs of the process can be achieved if conditions (4) are met

$$\begin{gathered}(\mu_c, \mu_s, h, F_c) \to max \\ (Q_s, F_n) \to min.\end{gathered} \quad (4)$$

In the course of further research, the authors optimized the diameter of the JSTDM confusor, the results of which are shown in Fig. 4 (Appendix E).

The analysis of the obtained results (Fig. 4) shows that in order to reduce the SEC of dispersion while ensuring the ADMFD of the product at the level (0.8 μm), it is necessary to use a confusor, the inner diameter of which is 3.5–4 mm. At the same time, the productivity of the disperser will be in the range of 1050–1400 l/h, and the SEC of homogenization will be 0.79–0.83 kW·h/t.

According to the developed methodology, graphs had been drawn to determine the optimal parameters of the disperser. The analysis of the optimization results (Fig. 5 (Appendix F)) shows that the use of a ring-shaped gap, the width of which is 0.6–0.8 mm, provides dispersion from ADMFD at the level of 0.8 μm with the lowest SEC of the process (Samoichuk, 2023; Samojchuk et al., 2019b). When using a gap, the width of which is equal to 0.9 mm, there is a trend towards a decrease in SEC. The highest values of energy consumption are observed when the width of the ring-shaped gap is 0.1 mm or less. With this version of homogenization and normalization using DPME with a fat content of 20%, to obtain a milk emulsion with a fat content of 3.5%, the SEC of the process increases by 35–40% compared to the other two options (h=0.5 and 0.9 mm).

From Fig. 5, it can be determined that in order to minimize SEC with a gap width of h=0.6–0.8 mm, it is rational to use DPME with a fat content of 33–43%. With such parameters, the SEC of dispersion is 0.88–0.92 kW·h/t (Samoichuk et al. 2020a; Samojchuk et al., 2019b).

In order to determine the rational value of the feeding speed and fat content of the cream, an optimization had been carried out, the results of which are shown in Fig. 6 (Appendix G). The analysis of the optimization results shows that it is necessary to use DPME with a fat content of 33–43%, while their feeding speed should be in the range of 7–11 m/s. In this case, the SEC of dispersion will have minimal values and will be in the range of 0.86–0.88 kW·h/t. When using DPME with a higher fat content (50%), an insignificant increase in the SEC of the process will be accompanied by high energy consumption during the homogenization of high-fat DPME before its use in JSTDM (Bulgakov et al., 2019a; Faichuk, 2022; Yanga, 2020). Reducing the fat content of DPME to 30% leads to an increase in the SEC of dispersion. This is due to the need (according to the material balance equation) to serve a larger amount of cream. The latter affects the need to increase the speed of feeding skimmed milk to create the maximum difference in the speeds of the dispersed and continuous phases, which is a necessary condition for effective dispersion.

When using DPME with a fat content of 10% and ensuring the specified ADMFD indicators, the SEC has the highest values and amounts to 1.04 kWh/t. Thus, the optimization of the parameters of JSTDM from the point of reducing the SEC while simultaneously ensuring high-quality dispersion is the supply of DPME with a fat content of 33–43%, in which the speed of the supply of DPME should not exceed 11 m/s (Samojchuk et al., 2019b).

The materials of the scientific article represent a logical continuation of research, the results of which were given in publications (Deynichenko, 2018; Samoichuk et al. 2020a; Samoichuk et al.. 2020c). Previously published data were devoted to the development of a method for determining the dispersibility of a milk emulsion, finding dependencies that would link the structural, technological, hydraulic parameters of the JSTDM with the ADMFD of dairy products and the SEC of dispersion (Samoichuk, 2023; Samojchuk et al., 2019b). A distinctive feature of the developed device is the possibility of creating the maximum difference in the speeds of the dispersed and continuous phases, which is a necessary condition for effective dispersion. This effect is achieved by feeding the DPME to the high-speed flow of skimmed milk through a ring-shaped gap of small width (Ansari, 2010; Graskemper, 2021; Samoichuk et al.. 2020a; Samoichuk et al., 2019a). The results of the analytical studies are confirmed by experimental data. They testify that when providing the product's FFC at the level of the standard of the regulatory documentation, the implementation of the JSTDM is able to provide a significant (up to 8 times) reduction in the SEC of the process (Deynichenko, 2018). The analysis of the results of the confusor diameter optimization in the place of the largest narrowing (Figure 4) indicates almost the same SEC when using the confusor, the diameter of which is in the range of values of 3.5–4.0 mm (0.79–0.83 kWh/ t) (Deynichenko, 2018; Panchenko, 2020; Samojchuk et al., 2019b). In significant up to 15–20% increase in energy consumption when using a confusor with a diameter at the point of the largest narrowing of 3 mm is explained by an increase in the required pressure of the dispersion phase supply.

A comparison of the obtained data with the closest in terms of design implementation of the JDMSSDP device had been carried out. In it, the cross-sectional area of the working chamber is a similar parameter to the width of the ring-shaped gap in the JSTDM (Samoichuk et al., 2019a). The recommended optimal value of this parameter for obtaining dairy products which ADMFD meets the standard of regulatory documentation is in the range of 3–6 mm^2 (Brodziak, 2021; Dhankhar, 2014; Samoichuk et al., 2019a). When ensuring the same productivity of 1,050–1,400 l/h, the SEC of JDMSSDP exceeds the indicators of JSTDM by 1.5...3 times (Malkina, 2022; Samoichuk, 2023). This is explained by the higher power values for driving the pumps for the DPME supply in the JDMSSDP, which make up the main part of the energy consumption during dispersion in it. The use of a ring-shaped gap instead of DPME supply channels made it possible not only to achieve a decrease in SEC in the JSTDM, but also to increase the reliability of the design (Samoichuk et al. 2020a).

The optimization of parameters of JSTDM (Fig. 5) and (Fig. 6) show that it is possible to obtain a milk emulsion with a fat content of 3.5%, the fat content of which is 0.8 μm (the width of the ring-shaped gap h=0.6–0.8 mm, diameter the confusor in the place of the largest narrowing d_c=3mm, the fat content of the DPME is in the range of 33–43%, the DPME feeding speed is 7–11 m/s).

At the same time, the SEC of the process is 0.86–0.92 kWh/t. For JDMSSDP, it is possible to obtain a milk emulsion with a fat content of 3.5%, the fat content of which is 0.8 μm, when using DPME with a fat content of 30%, with a diameter of the DPME supply channel of 0.8 mm. At the same time, the SEC is about 0.9 kWh/t (Samoichuk et al., 2019a). A comparison of the obtained results indicates a 6% reduction in energy consumption when using the JSTDM, which is explained by the increase in the DPME supply area, which is achieved when using a narrow ring-shaped gap in it (Ansari, 2010; Samoichuk, 2023; Voloshina, 2019).

Among the limitations of the conducted research, it should be noted that there is a lack of information on the optimal shape of the internal profile of the confusor surfaces. Conducting these studies and publishing the obtained results is planned in the next article. A potential consequence of an incorrect choice of form may be an increase in SEC during dispersion. Another consequence may be a change in the local hydrodynamic conditions in the area of the valve gap, which can potentially affect the dispersion efficiency in the JSTDM.

5. Summary and conclusion

1. Ukraine's integration into the European space, where the "Green deal" agreement was concluded, provides for the creation of a resource-efficient and competitive economy in the member states of the Union. Reducing the energy consumption of emulsion dispersion and homogenization processes, in particular in the dairy industry, is part of this process. Therefore, the article presents the results of research on the reduction of energy consumption of the jet-slot type disperser of milk, which reaches 90% compared to the energy consumption of a valve homogenizer.

2. The diameter of the confusor at the zone of greatest narrowing had been found to be optimal from the point of view of minimum SEC. The obtained results allow us to state that from the point of view of ensuring the reducing energy cost of dispersion, the width of the ring-shaped gap should vary in the range of 3.5–4.0 mm. With such values, productivity is ensured at a level close to industrial samples, and SEC has minimal values.

3. Optimization had been carried out in terms of the fat content of the DPME used in homogenization and the width of the ring-shaped gap. Research results show that the optimal value of the ring-shaped gap width, based on the conditions for ensuring the necessary dispersion while simultaneously reducing the SEC, is the range of 0.6–0.8 mm. The optimal values of fat

content of cream, which are used during normalization-homogenization in JSTDM, are 33–43%. When such parameters are set, the energy costs of dispersion are 0.88–0.92 kWh/t.

4. Determining the optimal values of the DPME feeding speed is of key importance for ensuring high reducing energy cost of dispersion in the JSTDM. Optimization of the DPME feed speed parameter made it possible to find the values of this parameter that provide the highest reducing energy cost of homogenization. The range of optimal values is 7–11 m/s.

The results of the research are of high practical value for the future development of an industrial energy efficient model of the jet-slot disperser and its implementation at the enterprises of the dairy industry.

At the same time, the limitations of the presented material include the lack of studies of secondary qualitative indicators of dispersion. Namely: histograms of the size distribution of fat globules, coefficients of size variation, indicators of stability (resistance to delamination) of the emulsion over time. After all, in the materials of this study, one main quality indicator was selected – the average diameter of fat globules of milk. Therefore, the further studies are planned to determine the value of the secondary qualitative indicators of of milk emulsion dispersion when the optimal design and technological parameters of the homogenizer are set, which are defined in this article. This will complete the research cycle of the jet milk homogenizer of the experimental type.

Author Contributions

Conceptualization, Kyrylo Samoichuk and Taras Hutsol; Methodology, Alexandr Kovalyov and Nadiia Palianychka; Data curation Serhii Komarnitskyi, Sylwester Tabor and Olena Bezaltychna; Visualization, Alexandr Kovalyov; Software, Maciej Kuboń and Taras Hutsol; Resources, Valentyna Kukharets; Validation, Kyrylo Samoichuk; Project administration Sylwester Tabor; Supervision, Taras Hutsol.

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Data availability

The datasets used and analysed during the current study available from the corresponding author on reasonable request.

Conflicts of interest

The authors declare that they have no known financial or personal conflicts of interest that could influence the work reported in this paper. Furthermore, all listed authors have reviewed and approved the final version of the manuscript.

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Appendix

Appendix A

Table 1. Comparative characteristics of promising dispersers.

Type of disperser	Average diameter of fat droplets after homogenization, μm	Average value of SEC, kWh/t
Valve	0.78	7.20
Microfluidizer	0.10	10.00
Cavitation	1.10	1.20
Mini-mixers	1.20	1.50
Opposite-flow jet	0.80	1.70
Impact-jet	0.82	1.50
Jet disperser with counter feed of cream	0.77	1.40
Jet disperser with separate supply of cream	0.85	0.88

Appendix B

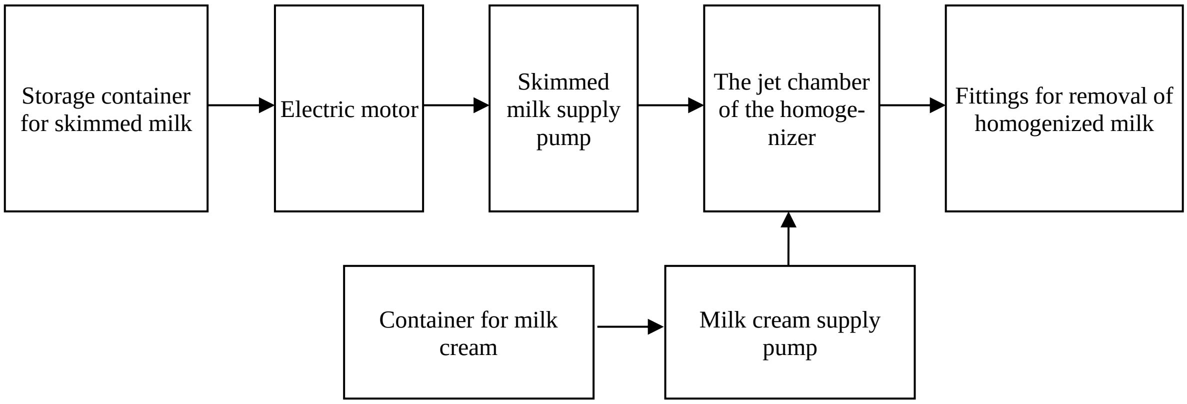

Fig. 1. Block diagram of a laboratory sample of a jet milk disperser.

Appendix C

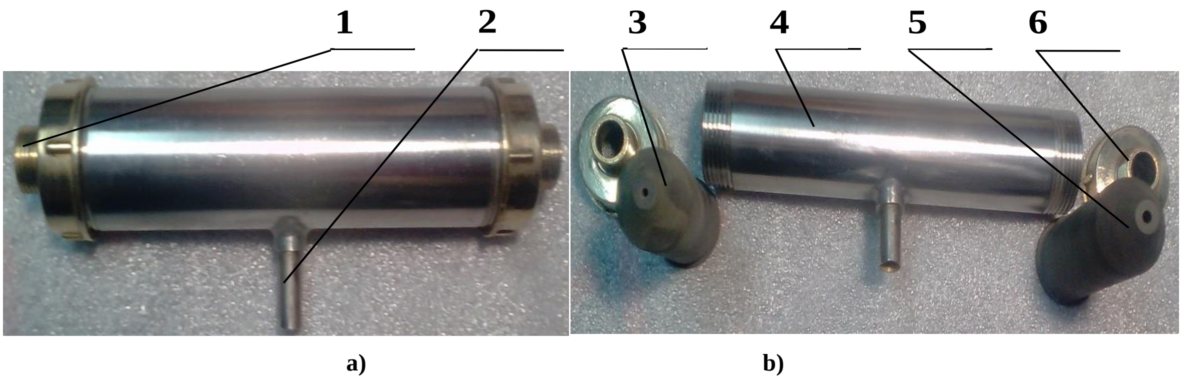

Fig. 2. The homogenization chamber of the slot-type jet milk disperser: a) assembled, b) internal structure. 1 – skimmed milk supply nozzle; 2 – nozzle for supplying the DPME from the container with cream; 3 – confusor; 4 – housing of the slot-type jet milk disperser chamber; 5 – diffuser; 6 – nozzle for removing homogenized and fat-normalized milk.

Appendix D

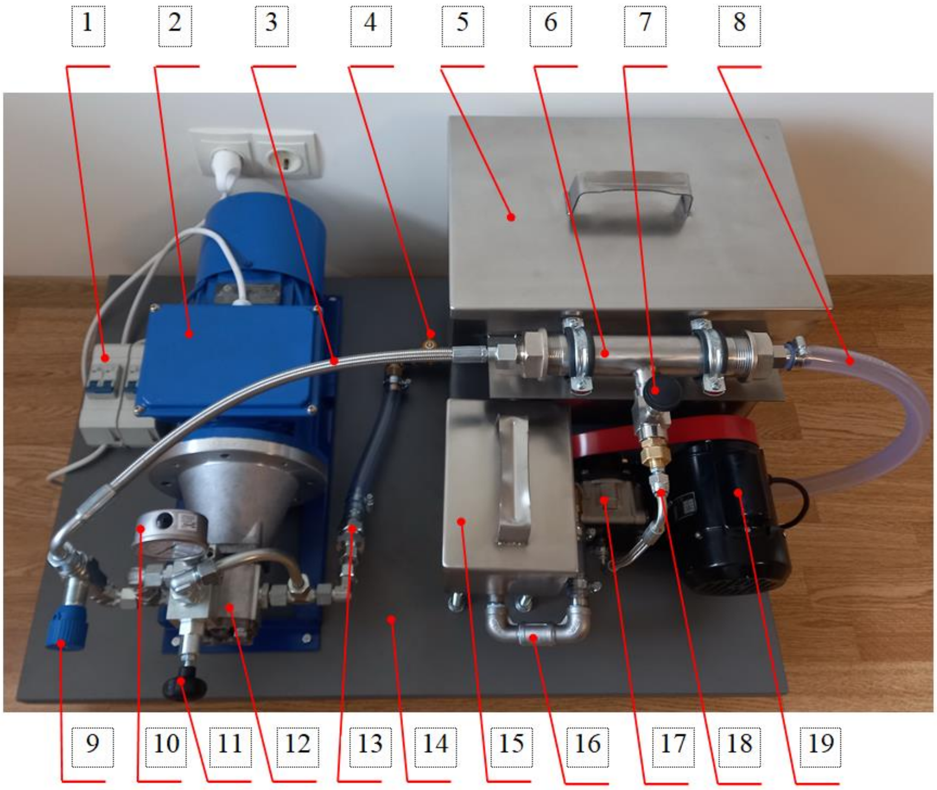

Fig. 3. Experimental installation of a jet-slot disperser of milk emulsions: 1 – electrical switches; 2 – the electric motor of the skimmed milk supply pump drive; 3 – high-pressure skimmed milk supply pipeline; 4 – skimmed milk supply valve; 5 – capacity of skimmed milk; 6 – jet chamber of the homogenizer; 7 – cream supply adjustment valve; 8 – finished product discharge pipeline; 9 – reduction valve; 10 – manometer; 11 – skimmed milk supply control valve; 12 – skimmed milk supply pump; 13 – low-pressure pipeline for the supply of skimmed milk; 14 – bed; 15 – container for cream; 16 – low-pressure cream supply pipeline; 17 – cream feed pump; 18 – high-pressure cream supply pipeline; 19 – electric motor for the cream supply pump drive.

Appendix E

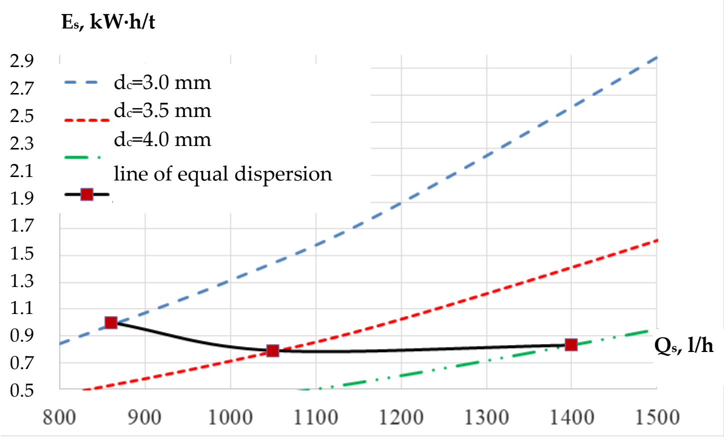

Fig. 4. Optimization of the diameter of the confusor of the jet-slot disperser of milk in the place of the largest narrowing d_c (at h=0.8 mm, μ_c=0.70, F_c=25%, μ_s=0.30, F_n=3.5%). The abscissa shows the interval of changes in the productivity of the jet-slot disperser for skimmed milk Qs, the ordinate shows the specific energy consumption of the device Es.

Appendix F

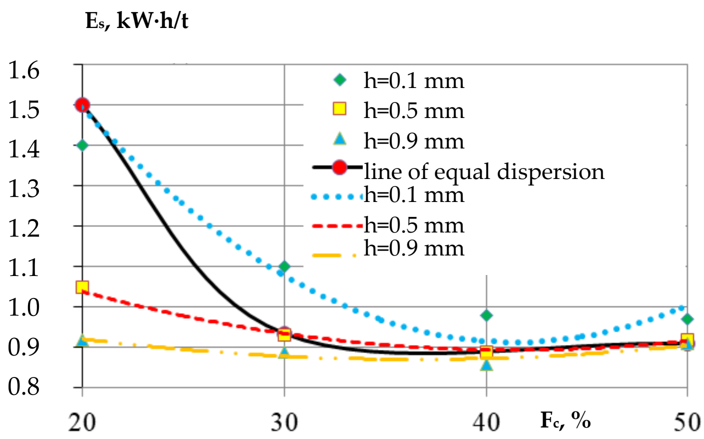

Fig. 5. Optimizing the fat content of DPME used in the normalization of skimmed milk to a fat content of 3.5% and the gap width in a jet-slot disperser of milk (at F_n=3.5%; μ_s=0.30; μ_c=0.98 d_c=3 mm; Q_s =1000 kg/h). On the abscissa axis, the interval of changes in the fat content of DPME F_c is given, on the ordinate axis, the specific energy consumption of the disperser E_s

Appendix G

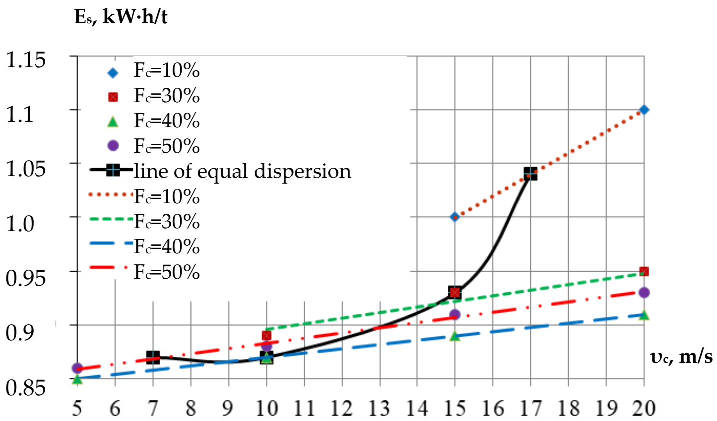

Fig. 6. Optimizing the speed and fat content of DPME used during normalization in a jet-slot disperser of milk (at F_n=3.5%; h=0.6mm; μ_s=0.30; μ_c=0.98, d_c=3mm; Q_s=1000 kg/h).