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Energy Costs Reduction for Dispersion Using a Jet-Slot Type Milk Homogenizer

Kyrylo Samoichuk [1,*], Alexandr Kovalyov [1], Natalia Fuchadzhy [1], Taras Hutsol [2,*], Michał Jurczyk [3], Tadeusz Pająk [3], Marian Banaś [3], Olena Bezaltychna [4] and Alona Shevtsova [5]

[1] Department of Equipment of Processing and Food Production, Technical Service and Systems in the Agro-Industrial Complex, Dmytro Motornyi Tavria State Agrotechnological University, 72-000 Zaporizhzhia, Ukraine
[2] Department of Mechanics and Agroecosystems Engineering, Polissia National University, 10-008 Zhytomyr, Ukraine
[3] Department of Power Engineering and Environmental Protection, AGH University of Science and Technology, 30 Adama Mickiewicza Al., 30-059 Krakow, Poland
[4] Department of Technology of Production and Processing of Livestock Products, Odesa State Agrarian University, Panteleimonivska Str. 13, 65-012 Odesa, Ukraine
[5] Innovative Program of Strategic Development of the University, European Social Founding, Faculty of Production and Power Engineering, University of Agriculture in Krakow, 30-149 Krakow, Poland
* Correspondence: kyrylo.samoichuk@tsatu.edu.ua (K.S.); wte.inter@gmail.com (T.H.)

Abstract: The priority task of the milk processing industry is in reducing the specific energy consumption of milk fat dispersion while simultaneously ensuring a high dispersion of milk emulsion. One of the possible ways to solve this problem is by developing and implementing a little-studied jet milk homogenizer of the slot type. In it, homogenization occurs by implementing the method of the separate feeding of cream, which allows creating the maximum difference between the speeds of skim milk and cream, which is a necessary condition for effective dispersion. Analytical dependences have been found that relate power and specific energy consumption to the performance of a milk homogenizer with the separate cream supply, the diameter of the annular gap, the fat content of normalized milk and cream, and the cream supply speed. The rational value of the fat content of the cream used for homogenization is analytically substantiated; in order to reduce the specific energy consumption of the process, their fat content should be higher than 20%. The most significant increase in the energy costs of dispersion is observed when processing milk with a fat content of less than 3–4%, while the use of cream with a fat content of less than 20% leads to a multiple increase in the energy costs of the process. The research results indicate the hyperbolic nature of the dependence of the homogenizer power on its productivity. Supplying the cream through an annular gap of small diameter allows reducing the main component of dispersion energy costs by eight times. The obtained data indicate the existence of a deviation within 5–10% of the experimental power values from the analytical ones, which is explained by the influence of the efficiency of pumps, drives, and losses in the connecting fittings.

Keywords: milk dispersing; specific energy consumption; power; fat globule; dispersion; jet homogenizer

Citation: Samoichuk, K.; Kovalyov, A.; Fuchadzhy, N.; Hutsol, T.; Jurczyk, M.; Pająk, T.; Banaś, M.; Bezaltychna, O.; Shevtsova, A. Energy Costs Reduction for Dispersion Using a Jet-Slot Type Milk Homogenizer. *Energies* **2023**, *16*, 2211. https://doi.org/10.3390/en16052211

Academic Editor: Helena M. Ramos

Received: 5 February 2023
Revised: 20 February 2023
Accepted: 22 February 2023
Published: 24 February 2023

1. Introduction

In raw milk, fat globules have a rather large average diameter, the value of which is 3–4 μm on average [1,2]. According to Stokes' law, fat globules of this size will rise to the surface in a fairly short period of time, forming a layer of cream [3]. This leads to a decrease in the dairy products shelf life which causes the loss of valuable milk fat on the walls of the container and the worsening of the products taste [1,4]. In order to prevent the listed consequences for the majority of the milk processing industry products, a regulatory operation—homogenization (dispersion of fat globules of milk emulsion, later dispersion)—is made. Its purpose is to reduce the average diameter of fat globules (ADFG) from 3–4 μm to 0.75–0.85 μm in the finished product [5]. Such dispersity is at the level of the regulatory documentation requirements, which regulates the quality indicators of dairy products after processing [6,7]. Dispersion due to the reduction of ADFG ensures a uniform distribution of cream in milk plasma [3].

Meanwhile, the most common in the industry valve homogenizers, which provide ADFG at the level of 0.75–0.80 μm, have too high specific consumption of electrical energy, reaching about 7–8 kWh/t of processed milk [8]. The percentage of energy costs for dispersing is about 30–40% in general technologies for the processing of milk and dairy products [9,10]. Therefore, reducing the energy intensity of the process is an urgent and important task for specialists in the processing industry and scientists by profession.

The study of homogenization in modern designs that ensure high energy efficiency of dispersion has made it difficult to visually observe the deformation and subsequent destruction of fat globules. This is explained by the high speed of milk movement (which exceeds 100 m/s for a valve homogenizer), the low degree of transparency of the milk emulsion, and the microscopic parameters of ADFG, which are about 1 μm [2]. The combined effect of these factors has resulted in the absence of a single theory of dispersal and has allowed researchers of the process to put forward about 10 hypotheses that have contradictions and that partially refute each other [1,4]. Designs created on the basis of these hypotheses either differ in high values of specific energy consumption (microfluidizers, valve) or do not provide a reduction of ADFG to 0.75–0.85 μm (vibration, electrohydraulic, vacuum) [2,5].

The results of recent studies allow us to single out Weber's criterion as the main factor for causing the deformation and destruction of fat globules. Its value increases with an increase in the sliding speed of fat globules relative to milk plasma. Therefore, the development of energy-efficient designs of homogenizers should be based on creating the maximum difference between the speeds of movement of skim milk and cream. Simultaneously, with the creation of favorable conditions for the destruction of fat globules, the principle to separate the supply of cream is used, which allows to reduce the energy costs of the process by 40–60% [1,3]. A group of jet milk homogenizers meets these requirements. Their use ensures a reduction of ADFG to 0.75–1.20 μm, while the specific energy consumption of such designs does not exceed 0.9–1.8 kWh/t [6,7,9]. Thus, conducting research on the destruction of fat globules in jet homogenizers represents a promising direction for increasing the energy efficiency of dispersion in the technological processes of the milk processing industry.

Recently, scientists have developed and researched a large number of jet type homogenizers, which indicate the high relevance of research into ways to increase the energy efficiency of the dispersion process. Among them are: impact-jet, volume disperser, hydrodynamic, cavitation, counter-current-jet, mini mixers of various shapes of the working surface, jet homogenizer with separate supply of cream, and microfluidizers [7,10].

The use of microfluidizers provides the highest dispersity of milk emulsion (ADFG about 0.1 μm and less, which are at the level of chylomicrons, and which easily enter the bloodstream and are quickly absorbed by the body) [11,12]. Despite the high dispersion of dairy products, microfluidizers have not been widely adopted [13]. This is due to the high specific energy costs of structures that exceed the costs of valve dispersers and their low productivity, which does not exceed 500 L/h [14,15].

The results of the latest research given in works [16,17] indicate that it is possible to achieve an increase in the energy efficiency of dispersion while ensuring productivity at the level of industrial homogenizers when using rhombic, Y-shaped, or T-shaped mini mixers. In them, skim milk in the required amount is supplied through channels located perpendicular to the central channel, through which the required amount of cream is supplied [18,19]. Research results indicate that the ADFG of milk when processed in mini mixers is 1.1–1.3 μm [20,21]. The energy consumption of such structures is moderate and amounts to 1.6–1.7 kWh/t [21,22]. It is practically impossible to further increase the energy efficiency of mini mixers. This is due to the fact that it must be ensured by increasing the speed of the liquid flow, which in turn will lead to an increase in energy costs for dispersion [23,24]. A possible direction of improvement could be the optimization of the shape of the surfaces of the internal channels of mini mixers [25,26]. However, according to studies [27,28], changing the profile of the internal surfaces of mixers does not provide a significant increase in the speed of the flow movement of skim milk. The low energy efficiency of mini mixers is explained by the insufficiently powerful influence of the flow of cream on the flow of skim milk [28–30].

The conditions necessary for the effective destruction of fat globules, namely the creation of the maximum difference between the velocities of the milk plasma and the fat globule, are achieved in an opposite-flow stream milk homogenizer [4,6]. Dispersion of the fat phase in homogenizers of this type is carried out by the collision of milk jets fed through two coaxially located nozzles. The structural features of the homogenizer design allow creating a high sliding speed of the fat globule in relation to the milk plasma [31,32]. This leads to increasing the values of Weber's hydrodynamic criterion, which causes the effective destruction of fat phase particles. According to research results [32], when processing milk in an opposite-flow stream milk homogenizer, the ADFG is about 0.75–0.85 μm, while its specific energy consumption does not exceed 1.6–1.8 kWh/t. However, when dispersing in this way, increased foaming is observed, which is associated with a violation of the stability of protein particles in milk due to its contact with air [6]. Such defects are inherent in shock-jet type homogenizers. In them, the destruction of fat globules occurs as a result of the collision of milk emulsion jets with the solid walls of different geometric shapes [33–35]. Research on homogenizers of this type was stopped due to the low energy efficiency of this design compared to devices of the countercurrent type [6,36].

The homogenizer developed on the basis of the cavitation hypothesis of dispersion of the fat phase of milk was predicted to increase energy efficiency. The principle of operation of such structures is described in the works [4,37] and consists of the creation of cavitation, which occurs as a result of the oscillation of the working organs or plates during their interaction with the milk flow. When using such designs, it is ensured that the ADFG is reduced to the level of 1.00–1.20 μm with a specific energy consumption of about 1.1–1.3 kWh/t of processed milk [38]. Research conducted by leading scientists [39] proved that cavitation does not have a decisive effect on the dispersion process and belongs to the secondary mechanism of fat globule destruction. This led to the impracticality of the further development of the theoretical foundations of dispersion when considering the cavitation phenomenon as the main driving force of the process [4,39].

In works [39,40], it is shown that one of the main ways of increasing the energy efficiency of dispersion is through the development of structures, the principle of operation which involves the separate dispersion of the fat phase of the milk emulsion. The design of a milk homogenizer with a counter supply of cream is known [41–43]. During its operation, after the preliminary separation of milk, a thin stream of cream is fed through a tube, which, according to the principle of operation, resembles a Pitot tube to the chamber, into which skim milk is fed at high speed. The use of such a design is predicted [6,36] to reduce the ADFG to 0.75–0.80 μm, which will be achieved due to the cumulative effect that will occur as a result of the collision of the flow of skim milk with the oncoming stream of cream. However, according to the results of analytical studies, this design is predicted to have a rather high specific energy consumption (about 1.3–1.5 kWh/t) [34,35]. This phenomenon will be explained by the need for additional energy expenditure to create the excess pressure necessary to prevent the Pitot tube from being pushed out [2,5].

One of these designs is a jet milk homogenizer with separate cream supply (JMHSCS). After preliminary separation, skim milk and cream are fed separately, a stream of cream is fed to the high-speed flow of skim milk [6]. Thanks to the use of thin cream supply channels and a small diameter of the jet, a high sliding speed of the fat globules is ensured. An increase in Weber's hydrodynamic criterion leads to a decrease in ADFG when using homogenizers of this type to 0.80–0.90 μm [44]. The use of the principle of a separate supply of cream ensures a reduction of the specific energy consumption of such structures to 0.85–0.90 kWh/t [6]. However, the use of thin channels for supplying cream (0.6–0.9 mm) leads to the rapid obliteration of their inner surfaces and reduces the reliability of the structure [41].

Therefore, possible ways to overcome the problem of insufficient energy efficiency of dispersing could be the use of a jet milk homogenizer with a separate supply of cream and a countercurrent-jet disperser. Meanwhile, the listed homogenizers have some disadvantages, including [36]:

- The presence of contact of milk emulsion with air, which leads to foaming, i.e., worsening the quality of the finished product;
- The implementation of the supply of the fat phase through channels of small diameter, which reduces the indicators of the reliability of the disperser.

In order to increase the energy efficiency of dispersion and eliminate the listed defects, the design of a jet-slot homogenizer of milk with a separate supply of the fat phase (JSHMSSFP) has been developed. The principle of operation of the developed device is based on separate dispersion, combining the possibility of normalizing milk by fat content with simultaneous homogenization, and the creation of the maximum difference in the speed of skim milk and cream; therefore, increasing the value of Weber's hydrodynamic criterion [44]. The use of JSHMSSFP has several advantages, including [45,46]:

- The ability to feed cream to the high-speed flow of skim milk in the form of a jet of small diameter, which will allow the flow to effectively act on the cream, ensuring the destruction of fat globules to the values justified by the requirements of regulatory documentation;
- The possibility of increasing productivity by increasing the volume of cream entering the homogenizer, which is achieved by changing the area of the slot channels (which also prevents equipment failure associated with rapid obliteration of the internal surfaces at the point of fat phase supply).

The results of the analytical studies of the parameters of JSHMSSFP show that when it is used, it is possible to obtain fat globules, the ADFG of which is 0.75–0.85 μm. At the same time, specific energy consumption will not exceed 0.70–0.80 kWh/t of processed products [45]. The work [42] determined the influence of the shape of the confusor at the point of greatest narrowing, determining the fat content of cream and normalized milk on the specific energy consumption of dispersion. However, the analytical determination of the effect of the fat content of the cream, the normalized mixture, or the shape of the internal surfaces of the confusor causes difficulties. This is due to the complex interaction of multiphase milk emulsion jets, which is observed when using a jet-slot type disperser [45]. Computer modeling methods are usually used to solve such problems. However, taking into account the lack of a general theory of dispersion, computer models that adequately describe the homogenization process have not yet been developed [47]. This fact allows us to affirm the expediency of conducting research devoted to determining the influence of structural, technological and hydraulic parameters on the energy costs of the JSHMSSFP. The materials of these studies will make it possible to optimize the parameters of the JSHMSSFP and conduct an assessment of the economic efficiency of the implementation of the developed design to increase the energy efficiency of dispersion.

The purpose of the research presented in this article is to increase the energy efficiency (reduction of power and specific energy consumption) of the emulsion dispersion process due to the development of an energy-efficient jet-slot milk homogenizer.

The obtained results will create an opportunity to determine the optimal parameters of the JSHMSSFP for increasing the energy efficiency of the dispersion process.

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

- To find analytical dependences that link the power and specific energy consumption with the productivity of the homogenizer, the diameter of the annular gap, the fat content of normalized milk and cream, and the speed of cream supply;

- To determine the effect on the energy consumption of the fat content of normalized milk and cream and to find a rational value of the fat content of cream used during normalization and homogenization in a jet-slot homogenizer of milk;
- To develop a methodology and conduct experimental studies on the dependence of the developed homogenizer power on its performance, to check the adequacy of the analytically obtained data.

2. Materials and Methods

The homogenizing unit of the jet-slot milk homogenizer, the diagram of which is shown in (Figure 1), consists of a skim milk supply nozzle 1, a confusor 2, an annular gap 3, a container with cream 4, a diffuser 5, and a homogenized milk discharge nozzle 6 [44]. After preliminary skimming, the milk at a high speed υ_s enters the homogenizing unit through the supply nozzle 1. At the place where the mixer 2 has the smallest diameter d_k, the skim milk flows through the annular gap 3, which has a small width h, from the container with cream 4, at a speed υ_c cream. Feeding cream at a much lower speed than skim milk makes it possible to create a high sliding speed of the fat globule relative to the milk plasma, as a result of which, the value of the Weber criterion increases [45]. As a result of active hydrodynamic effects acting on the fat globules in the area of the transition to the expansion of the diffuser 5, their destruction occurs, after which the homogenized milk is discharged through the nozzle 6.

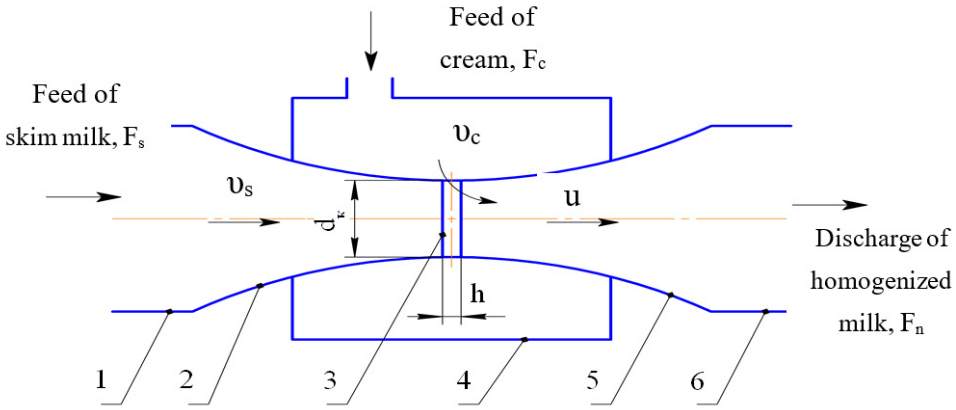

Figure 1. Scheme of the homogenizing unit of the jet-slot homogenizer of milk with a separate supply of the fat phase: 1—the supply pipe of skim milk; 2—confusor; 3—annular gap; 4—container with cream; 5—diffuser; 6—homogenized milk discharge nozzle; F_s—fat content of skim milk; υ_s—speed of supply of skim milk; d_k—the diameter of the confusor at the point of greatest narrowing; h is the width of the annular gap; υ_c—cream feeding speed; F_c—fat content of cream; u—sliding speed of fat globules relative to milk plasma; and F_n—fat content of milk after normalization and homogenization.

Due to the possibility of supplying the necessary amount of cream and skim milk, the developed device allows combining the simultaneous normalization of milk by fat content and dispersion of the fat phase of milk emulsion. Therefore, the rate of supply of skim milk, cream, the fat content of skim milk and cream, and the width and length of the annular gap can be found from the ratio obtained during analytical studies for the processing of dairy products of the required fat content in JSHMSSFP [43].

Before having developed the design of the jet-slot milk homogenizer, the authors had developed a technological scheme of its operation (Figure 2).

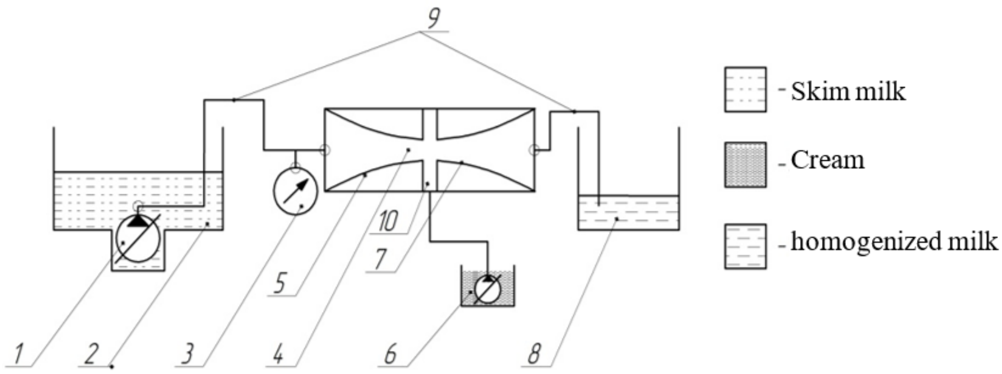

Figure 2. Technological scheme of the homogenizer for dispersing the fat phase of milk emulsion: 1—gear pump for supplying skim milk; 2—container for skim milk; 3—manometer; 4—place of greatest narrowing; 5—inner surfaces of the confusor; 6—gear pump for supplying cream; 7—inner surfaces of the diffuser; 8—container for draining the processed product; 9—flexible pipelines; and 10—ring slot for feeding the fatty phase.

During the operation of the jet-slot milk homogenizer, pre-skim milk from the container 2 (Figure 1) is fed through the pipelines 9 with the help of the pump 1 under pressure, the value of which is monitored with the help of the manometer 3 to the place of the largest narrowing 4, which is created by the profiled inner surfaces of the confusor 5 and the diffuser 7. At the place of the largest narrowing, the necessary amount of cream is fed to the skim milk, which moves at a high speed from a special container with the help of a pump 6 through the annular gap 10. In the mode of developed turbulence, significant tangential stresses act on the fat globule, which arise due to the action of the forces of resistance to the movement of the fat globule. These stresses are related to Weber’s criterion, and when their values exceed the forces of interfacial tension, they cause the fat globule to break into several smaller formations [6,7].

In order to check the adequacy of the dependences obtained analytically, as well as to conduct experimental studies, a laboratory installation of JSHMSSFP had been developed (Figure 3). It was created 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 Agrotechnologycal University (Ukraine). During the operation of the device, skim milk from container 8 flows through flexible pipeline 1 to gear pump 2. It is actuated when the electric three-phase motor 5 is started, which starts working when the package switch 4 is turned on.

With the help of pump 2, skim milk is fed through pipelines 6 to the homogenizing unit 9. Control of the working pressure of the supply of skim milk is carried out using a manometer 12, and the hydraulic parameter of the process itself is changed by closing the throttle valve 11. At the place of the greatest narrowing of the homogenizing unit 3 through a flexible hose 10, cream is fed from the container with cream 3 by means of the food pump 7 of the rotary type. The cream feed pump is driven by turning on the power source 16 to the electrical network, and subsequently starting the tumbler 15. The supply of the required amount of cream and the adjustment of the rotation frequency of the motor of the feed pump drive is ensured by means of a built-in potentiometer with a regulator 13. Normalized fat and homogenized milk is directed to a special storage tank by means of a flexible hose 14 [44,48].

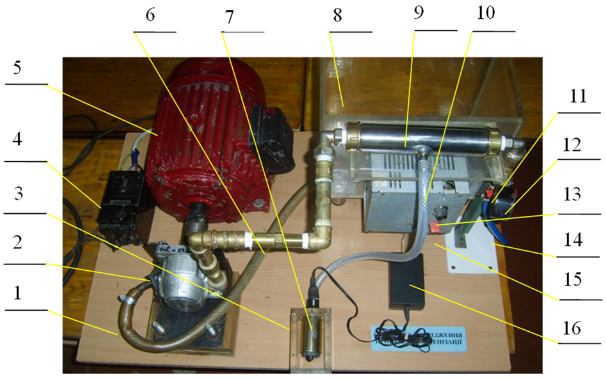

Figure 3. Laboratory installation of a jet-slot milk homogenizer: 1—a flexible pipeline for supplying skim milk; 2—gear pump; 3—container with cream; 4—packet switch; 5—electric three-phase motor; 6—pipeline; 7—cream feed pump; 8—container with skim milk; 9—homogenizing node; 10—a flexible hose with a clamp for supplying cream; 11—throttle valve; 12—manometer; 13—potentiometer with regulator; 14—flexible hose for removing homogenized milk; 15—switch for starting the cream feed pump; and 16—electric drive of the cream feed pump.

The cow's milk used for experimental research meets the requirements of ISO 9622: 2013 (Milk and liquid milk products) [49]. Sampling was performed in accordance with the provisions of ISO 707: 2013 (Milk and milk products. Guidance on sampling) [50].

Fractional distribution of ADFG after homogenization was determined using an optical microscope Mikromed P-1-LED. The total multiplicity of its increase is 1500 times. A digital camera with a resolution of 640x480 Mustek Wcam 300 (Taiwan) was used to visualize the dispersed composition of the milk emulsion on the monitor screen and further process the image [51]. Each experiment was performed in triplicate.

The temperature of skim milk, the optimal values of which are 60–65 °C [42,43], and cream, the recommended temperature of which should be in the range of 35–40 °C [1], are among the constant factors of the dispersion process in JSHMSSFP.

The process variables include the width of the annular gap, the speed and fat content of the cream, the excess pressure of the skim milk supply and the performance of the homogenizer.

The range of variation in productivity of the jet-slot homogenizer of milk had been chosen based on the condition of its provision at the level of industrial samples and varied in the range of 400–1600 L/h [7].

From the point of view of ensuring the quality of dairy products at the level of the requirements of regulatory documentation, the excess pressure of the supply of skim milk should be in the range of 1–3 MPa. The lower limit of the range is justified by the need to ensure sufficiency for dispersing the difference in phase speeds and the condition of ensuring performance close to industrial samples. The upper value of the range marks the limit beyond which a multiple increase in the energy costs of dispersion is observed [6,41].

In order to increase the degree of dispersion of the emulsion, one should strive to reduce the zone with a reduced sliding speed of fat globules, and therefore to use the minimum possible width of the annular gap, which is 0.1 mm. However, excessively low values of the width of the annular gap can lead to a decrease in the reliability of the developed homogenizer. Since the cross-sectional area of the annular gap of the homogenizer has values close to the total area of the cream supply channels in the closest type of construction of the jet milk homogenizer with separate cream supply (JMHSCS), the upper value of the variation range of this factor is 0.9 mm [6].

The fat content determines the percentage of fat in the total volume of the dispersed phase and determines the distance between the fat globules in it. The range of variation of this factor had been selected taking into account the parameters of the closest in terms of the design of the JMHSCS. For this homogenizer, the fat content of the cream during the research varied in the range of 10–50% [7,42]. The lower limit of the specified range is justified by a significant increase in energy consumption, which is explained by the need to feed cream with a fat content of less than 10% at a higher speed to ensure the specified fat content of the dairy product. On the other hand, the use of cream with a fat content of more than 50% is also irrational, due to the significant increase in energy costs for additional dispersion when using high-fat cream.

The range of variation in the speed of cream feeding is justified on the basis of the formulated hypothesis of dispersion. According to this hypothesis, an effective reduction of ADFG while reducing energy costs can be achieved by creating the maximum difference between the rates of skim milk and cream [6,7]. The lower limit of the range (5 m/s) is determined based on the condition of ensuring the minimum speed of cream supply through the annular gap of the homogenizer. The upper limit of the range (110 m/s) is justified by a significant increase in electricity consumption, since in this case the process will proceed according to the principle of valve homogenizers with a corresponding increase in energy consumption.

When conducting experimental studies, the range of variation of variable factors [45,46]:

- The excess pressure of the supply of skim milk (1–3 MPa);
- The width of the annular gap (0.1–0.9 mm);
- The speed of cream (5–110 m/s);
- The fat content of cream (10–50%).

Dispersion quality is determined by the amount of ADFG and the width of the polygon, which corresponds to the distribution of the fractional composition of the milk emulsion [52].

The means of control had been determined, so the authors measured:

- The duration of the experiment which was determined by a stopwatch SOPR-2a-2-010 (Russian Federation), with an absolute error of no more than 0.2 s;
- The weight of milk which was determined on an electronic scale SCL-150 (Taiwan), with an absolute error of no more than 5 mg;
- The temperature of the skim phase and cream which was determined by a thermometer with an interchangeable cone, with an absolute error of no more than 0.5 °C.
- The power using a McBrain VA318 electrical measuring wattmeter with an absolute error of 0.1 V.

Productivity Q in terms of the volume of liquid that arrived after homogenization to the storage tank can be found using the formula [1]

$$Q = \frac{m}{\rho_n t}, \tag{1}$$

where

m—weight of homogenized milk, kg;

ρ_n—density of normalized milk, kg/m^3;

t—homogenization time, s.

The power of the pump drives used to drive the skim milk supply pumps P_s and cream P_c can be determined from the dependences [42,43]

$$P_c = Q_c \cdot \Delta p_c, \tag{2}$$

$$P_s = Q_s \cdot \Delta p_s, \tag{3}$$

where Q_c, Q_s—respectively, the productivity of the jet-slot homogenizer for cream and skim milk, kg/h;

Δp_s, Δp_c—accordingly, the supply pressure of skim milk and cream, MPa.

The total power of the homogenizer is determined from the following formula [43]

$$P = P_s + P_c. \tag{4}$$

The specific energy consumption E_s of the jet-slot homogenizer of milk was determined as [41]

$$E_s = \frac{P}{Q}. \quad (5)$$

After conducting experimental studies, optimization was carried out in order to establish rational values of the parameters of the JSHMSSFP.

3. Results

3.1. Results of Analytical Studies of Power and Specific Energy Consumption in a Jet-Slot Milk Homogenizer

Conducted research on the quality of dispersion in the developed jet-slot milk homogenizer shows that during milk processing, it is possible to obtain ADFG at the level of 0.75–0.85 μm at a cream speed of 40 m/s and less, a cream fat content of 40–50%, and an annular width gap of 0.1–0.5 mm [7,45]. At the same time, the coefficient of variation of JSHMSSFP is 15%, which is lower than similar indicators for valve homogenizers by 17% [45].

The capacity of a jet homogenizer with a separate feed of the fat phase is determined from dependence (4), which, taking into account (2), (3) and the material balance equation, can be represented in the form (6)

$$P = Q_s\left(\Delta p_s + \frac{(F_n - F_s)}{F_c - F_n}\Delta p_c\right). \quad (6)$$

Taking into account the known relations [1,34,35] that establish the relationship between excess pressure and dispersion speed, after transformations, we obtain analytical expressions for calculating the excess pressures of the supply of skim milk and cream in JSHMSSFP

$$\Delta p_s = \frac{8 \cdot {Q_s}^2 \cdot \rho_s}{{\mu_s}^2 \cdot \pi^2 \cdot {d_k}^4}, \quad (7)$$

$$\Delta p_c = \frac{{Q_c}^2 \cdot \rho_c}{2{\mu_c}^2 \cdot \pi^2 \cdot d_k^2 \cdot h^2}, \quad (8)$$

where ρ_s, ρ_c—respectively, the density of skim milk and cream, kg/m^3;

μ_s, μ_c—respectively, the flow rates of the confusor at the place of the largest narrowing and the annular gap at the place where the cream is fed;
d_k—diameter of the confusor at the point of greatest narrowing, mm.

The power of the jet-slot homogenizer, taking into account the dependences (4), (6), (7), (8) and the known ratio between the supply of cream and skim milk, can be represented in the form [7,53,54]

$$P = {Q_s}^3\left(\frac{8\rho_s}{2{\mu_s}^2\pi^2{d_k}^4} + \left(\frac{F_n - F_s}{F_c - F_n}\right)^2 \frac{\rho_c}{2{\mu_c}^2h^2\pi^2 d_k^2}\right). \quad (9)$$

The dependence of the capacities of the skim milk, cream and total capacity pumps on the supply of skim milk is hyperbolic (Figure 4). The analysis of the obtained results shows that the power of the skim milk supply pump at Q_s = 1000 L/h, and the gap width equal to 0.6 mm, is 8 times higher than the power of the pump used to supply cream.

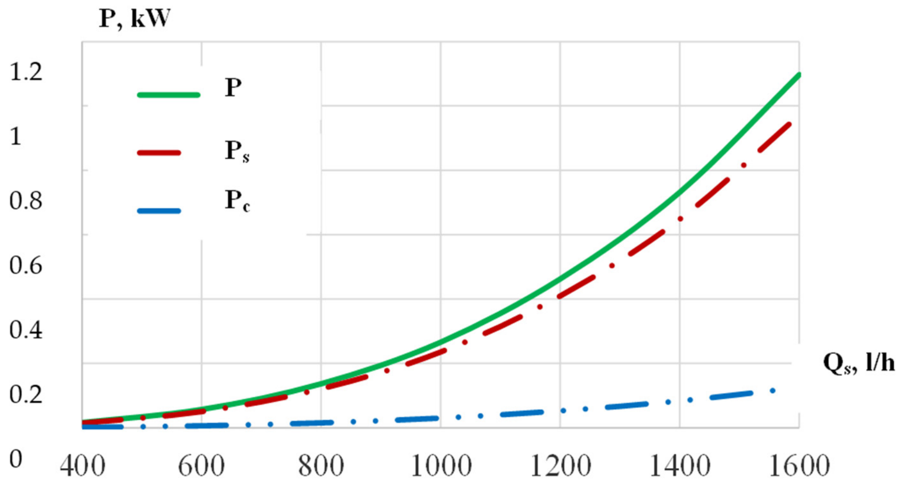

Figure 4. Dependence of the capacity of the cream, skim milk supply pumps and the total capacity of the JSHMSSFP Pc, Ps, and P on the supply of skim milk Qs (at d_k = 3 mm; μ_k = 0.95; F_n = 3.5%; F_s = 0.05%; F_c = 40%; h = 0.6 mm; μ_B = 0.3).

The specific energy consumption of the jet-slot homogenizer is determined from the formula [43,52]

$$E_s = \frac{Q_s \cdot \Delta p_s + Q_c \cdot \Delta p_c}{(Q_c + Q_s) \cdot \rho_n}, \tag{10}$$

or taking into account (7), (8) and the material balance equation, we get

$$E_s = \frac{\Delta p_s \left(8 \cdot \rho_s + \frac{\mu_\kappa^2 \cdot d_k^2 \cdot \rho_c}{2 \cdot h^2 \cdot \mu_c^2} \left(\frac{F_n - F_s}{F_c - F_n}\right)^3\right)}{8 \cdot \rho_s \cdot \rho_n \cdot \left(\frac{F_c - F_s}{F_c - F_n}\right)}. \tag{11}$$

A decrease in the fat content of normalized milk leads to a decrease in the specific energy consumption of dispersion (Figure 5), since, at the same time, a lower pressure of normalized milk is required for the destruction of fat globules, and therefore a lower rate of supply of the fat phase. The dependence analysis indicates a significant increase in specific costs of dispersion when used to normalize cream, the fat content of which does not exceed 20%.

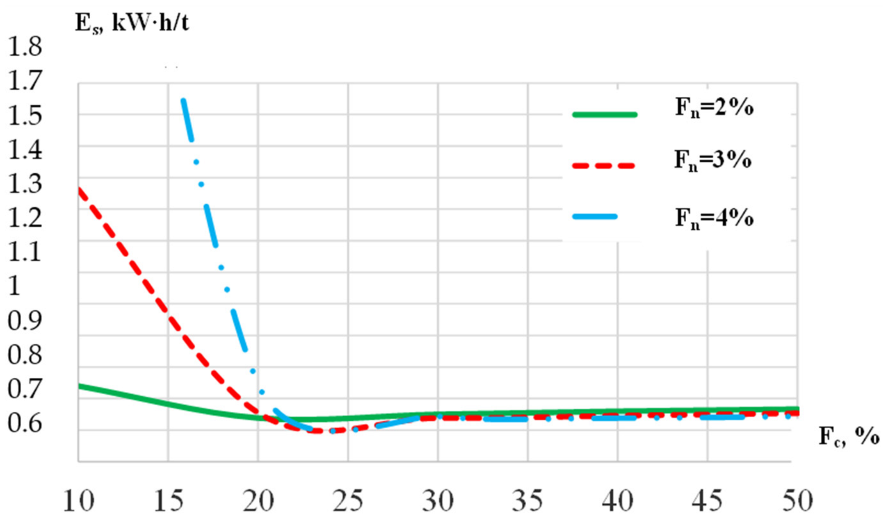

Figure 5. Dependence of the specific energy consumption E_s on the fat content of cream F_c and normalized milk F_n (at d_k = 3 mm; F_s = 0.05%; h = 0.5 mm; μ_B = 0.3; Q = 1000 kg/h, μ_k = 0.98).

The nature of the obtained dependence is explained by the fact that in order to ensure the necessary initial fat content of homogenized milk, it is necessary to ensure the injection of cream through a narrow annular gap, which naturally leads to an increase in pressure, and therefore specific energy consumption of the process [7,55–57].

3.2. Experimental Study of Power in a Jet-Slot Homogenizer of Milk

In the course of further research, the capacity of the pumps providing the supply of skim milk and cream and the total power spent on the operation of the JSHMSSFP has been found, as shown in Figure 6.

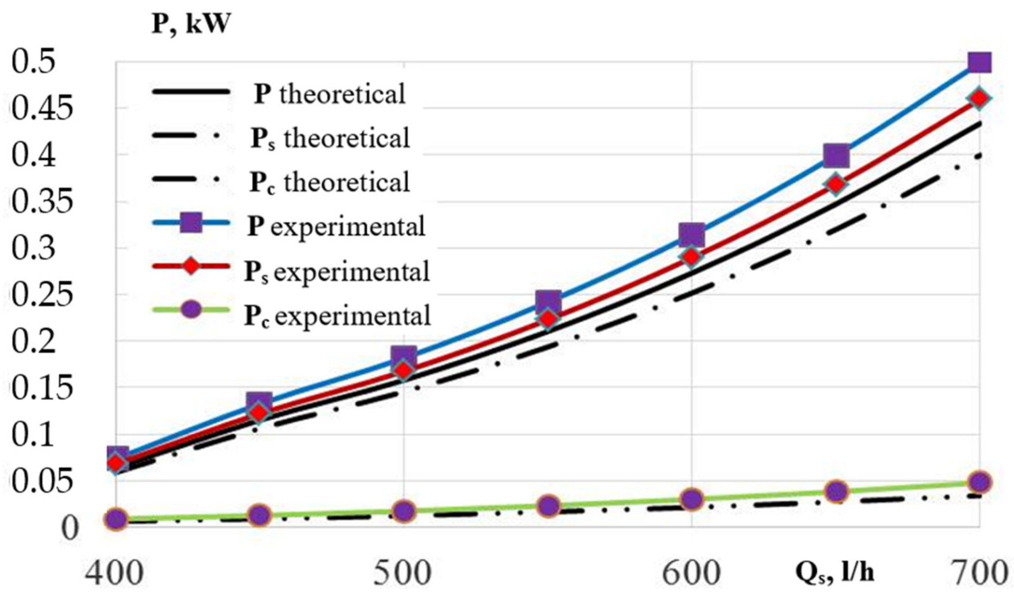

Figure 6. Graph of the dependence of the capacity of pumps for supplying skim milk, cream, and total capacity on the performance of the jet-slot milk homogenizer.

The analysis of data from the experimental studies of power consumption for the operation of the JSHMSSFP (Figure 5) indicate the consistency of the obtained data with the results of analytical studies (Figure 3). The slight difference in the experimental data, which exceed the analytical values, is explained by the loss of power, taking into account the efficiency of drives and pumps [56].

4. Discussion

The results presented in the article are a continuation of the research published in articles devoted to the justification of the methodology for determining the quality of dispersion, analytical, and experimental studies of the parameters of JSHMSSFP [7,42–44,55–57]. Characteristic features of the jet-slot type milk homogenizer include the possibility of supplying a thin stream of cream to the high-speed flow of skim milk, which is realized when using a narrow annular slot in the JSHMSSFP [7]. The practical implementation of this method can provide a significant (up to 7–8 times) reduction in the specific energy consumption of the process when obtaining a product whose ADFG is at the level of the requirements of regulatory documentation [1,31–33]. Limitations in conducting the research include the lack of fixation of the stages of destruction of fat globules during dispersion in the form of microphotographs. These difficulties are related to the microscopic size of the particles of the dispersed phase and the high speeds of movement of skim milk and cream in the JSHMSSFP [45].

The results of research on the power dependence of the developed homogenizer at different values of skim milk productivity (Figure 3) show that with the width of the annular gap h = 0.6 mm and Qs = 1000 kg/h, the power of the pump for supplying cream is 8 times less than the power of the pump for supplying skim milk. Such data have significant differences from the results of the study of the jet milk homogenizer with separate cream supply (JMHSCS), which is the closest in principle to the JSHMSSFP in terms of its action. In it, with the diameter of the cream supply channel d_k = 0.8 mm, the power of the pump used to supply the dispersed phase is 5.5–5.7 times higher than the power of the pump designed to supply the dispersed phase [6,40]. Discrepancies in the results are due to the fact that in the case of JMHSCS, in order to create the necessary phase speed difference for dispersion, it is necessary to ensure the supply of cream through a channel or channels of small diameter, which increases this component of the total energy consumption of this homogenizer. The confirmation of such conclusions is the fact that when the diameter of the cream supply channel is reduced to d_k = 0.2 mm, the total power of the JMHSCS increases by 17–18 times [41], despite the fact that the dependence of power on skim milk productivity is hyperbolic for both types of homogenizers. However, with the same productivity Qs = 1000 kg/h, the power of the JMHSCS (1.2 kW) is 6 times higher than the total power of the JSHMSSFP (0.2 kW), which indicates the high energy efficiency of the developed design [9].

The dependences of specific energy consumption on the fat content of cream for different values of normalized milk have a similar character for JSHMSSFP and JMHSCS. At the same time, in the developed homogenizer, the specific energy consumption of dispersion (Figure 4) increases when using cream, the fat content of which is less than 20–25%. This is explained by the need to feed more cream of lower fat content, which, when using an annular gap with a width of h = 0.5 mm, leads to an increase in the necessary dispersion pressure, and therefore in the specific energy consumption of the process [44]. For JMHSCS, the range of cream fat, below which a significant increase in the specific energy consumption of the process is observed, is 20–30%. If we compare the specific energy consumption of JSHMSSFP and JMHSCS when the fat content of normalized milk F_n is 3.5% and the fat content of cream F_c is 20%, it should be noted that the energy consumption of the first is about 1.2 kWh/t while the second is 1.5 kWh/t, which is explained by the use of the developed design of an annular gap instead of cream supply channels [41,42].

The analysis of the power graphs of JSHMSSFP drives (Figure 5) shows the existence of a correlation between analytical and experimental power data. At the same time, the latter exceed the theoretical indicators at the level of 5–10%, which is explained by the presence of losses in the connecting fittings, homogenizer nozzles, as well as taking into account the efficiency of the pumps and drives of the JSHMSSFP [5]. A comparison of the obtained data at the same performance with the results of experimental studies of the capacity of JMHSCS shows that the indicators of the developed homogenizer are exceeded by 15–20% [41]. This is explained by the use of several channels in the JMHSCS for supplying cream, which allows to reduce the main component of the energy costs of dispersion.

Prospects for further research have been planned:

- To determine the optimal parameters of the developed homogenizer: a high degree of dispersion with minimal energy consumption;
- To establish the effects of obliteration and experimentally determine the real coefficient of consumption of the annular gap. After conducting such studies, it will be possible to develop technical documentation for the introduction of the experimental homogenizer into production.

5. Conclusions

1. Analytical dependences have been found that relate the power and specific energy consumption to the performance of the homogenizer, the diameter of the annular gap, the fat content of normalized milk and cream, and the rate of cream supply. These dependences are the basis for creating the theory of jet dispersion of microemulsions. The theoretical significance of the obtained results lies in the improvement of the theory of hydrodynamic dispersion of milk emulsions.
2. The rational value of the fat content of the cream used for homogenization is analytically substantiated. The nature of the obtained analytical dependences indicates a

significant increase in the energy consumption of dispersion when using cream with a fat content of less than 20%, which is associated with an increase in the volume of cream fed through the annular gap during the normalization-homogenization of milk. To minimize the specific energy consumption of the process, their fat content should be higher than 20%. In the experimental homogenizer, it is possible to carry out the process of fat normalization simultaneously with homogenization. In this case, the fat content of cream can be less than 20% when producing milk with a fat content of less than 2%.

3. Experimental studies had been conducted, the results of which confirm the adequacy of the data obtained in the course of analytical studies. Thus, the deviations of the power indicators of the developed jet-slot homogenizer of milk differ from the data obtained in the course of analytical studies by not more than 10%. Thus, the developed analytical dependences can be used to calculate industrial samples of jet milk homogenizers. The practical significance of the conducted research consists of substantiating the possibility of a 5–7-fold reduction in energy costs when implementing a jet-slot homogenizer of milk at enterprises in the milk processing industry.

Author Contributions: Conceptualization, K.S. and A.K.; methodology, N.F. and T.H.; software, M.J. and T.P.; validation, M.B. and O.B.; formal analysis A.S.; supervision, T.H. All authors have read and agreed to the published version of the manuscript.

Funding: Financed from the subsidy of the Ministry of Education and Science for the AGH University of Science and Technology for the year 2023.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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