CHAPTER 3

Analysis of the hypotheses of milk fat phase dispersion and structural features of homogenizers

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Abstract

We have carried out the analysis of hypotheses, mechanisms, prevailing hydrodynamic factors of the milk emulsion fat phase dispersion, hydrodynamic conditions of milk fat globules disruption in the modern designs of dispergators and methods of analysis of the equipment for micro emulsions homogenization.

It points out a wide range of designs of homogenizers and a large number of existing hypotheses of milk emulsion dispergating that contradict each other.

Despite substantial differences, the general features of designs which allow receiving a high degree of dispergating is to create hydrodynamic conditions to provide increasing relative velocity of movement of the fat globule and acceleration of the emulsion stream.

Analysis of methods of intensifying the dispergating process of milk emulsions resulted into distinguishing prospective ways to increase energy efficiency of homogenizers and designs with the biggest potential for diminishing energy consumption.

Keywords

Milk homogenization, hydrodynamic factors of emulsions dispersion, design analysis of homogenizers, principle of homogenizer action, homogenization hypotheses, classification of homogenizers, mechanisms of milk fat globules disruption, homogenization intensification methods.

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3.1 Introduction

The milk homogenization is understood as the process of its processing which leads to the dispersion of the fat (dispersed) phase and its uniform distribution over the volume of the dispersed phase [1].

Today, the vast majority of milk as a raw material for the production of drinking milk, cream and other types of dairy products is subjected to homogenization. The main advantages of products produced using homogenization are given in **Table 3.1** [1, 2].

Table 3.1 Advantages of homogenized dairy products

Type of dairy products	Advantages of the product after homogenization
Whole milk after milking	Reduction of the development of oxidation processes, destabilization and whipping during intensive mixing and transportation
Pasteurized milk and cream	Providing uniformity of color, taste, fatness. Improving the consistency, increasing the intensity of white color. Reduction of fat film during boiling, which preserves milk solids. Increase in digestibility (homogenized milk corresponds to boiled milk in terms of fat digestion)
Sterilized milk and cream	Increased stability during storage. Reduction of fat deposition
Sour milk products (sour cream, kefir, yogurt, etc.)	Increasing the clot strength, stability and improving the consistency of protein clots, increasing the viscosity, reducing the whey secretion
Canned condensed milk	Prevention of the separation of the fat phase during long-term storage
Dry whole milk	A decrease in the amount of free milk fat, not protected by protein shells, which leads to its rapid oxidation under the influence of atmospheric oxygen
Reconstituted milk, cream and fermented milk drinks	Better taste of the product and prevention of the appearance of a watery aftertaste
Milk with fillers	Improves taste, increases viscosity and reduces the likelihood of sediment formation
Some hard cheeses	Facilitating the access of mold lipases to milk fat during cheese ripening
Some cheeses from recombined milk and some fresh fermented milk cheeses (creamy, etc.)	Preventing the deposition of a fat layer during a relatively long period of gel formation, contributing to the improvement of product homogeneity, as well as the formation of a loose and brittle texture
Milk mixtures for the ice cream production	Improvement of whipping of mixtures for the ice cream production, its structure and homogeneity

In addition to the dairy industry, the preparation of highly dispersed emulsions, which are stable for a long time, is widely used in the preparation of:

– mixtures for ice cream (preparation of the mixture "milk base – vegetable fat");

– mayonnaise, margarine, ketchup, etc. products;

– non-stick emulsions (layers) for greasing bread molds and sheets;

– emulsions for surface treatment of agricultural products – creation of a film-forming protective layer on their surface;

– cooked sausages, when raw fat is added to the minced meat in the form of a water-fat emulsion;

– dough when emulsion is introduced instead of fat, thanks to which up to 90 % of fat is preserved;

– cosmetic and pharmacological preparations, in which emulsions are absorbed faster by the body, soften the irritating effect of the ingredients;

– medicinal oils that lose unpleasant taste and smell;

– obtaining an emulsion based on the use of skimmed milk by adding fat and other necessary ingredients during the production of whole milk substitutes.

In addition to the advantages, the homogenization of dairy products also has disadvantages:

– increase in the cost of the product;

– increased sensitivity to light, which leads to taste defects, such as rancidity, soapiness and oxidation;

– milk becomes unsuitable for the production of many types of hard cheeses, due to too soft coagulation and difficulty in releasing moisture;

– whole milk is not suitable for homogenization due to the rapid deterioration of the aroma due to the action of lipase.

3.2 Properties of milk emulsion as an object of hydrodynamic dispersion and homogenization

The dispersion phase of milk emulsion is milk plasma, which is a solution of milk sugar and salts in water. Some authors [3, 4] distinguish a third phase of milk – the protein phase, consisting mainly of insoluble casein micelles and submicelles, as well as whey proteins.

Special attention is not paid to the uniformity of the distribution of microscopic fat particles due to their constant (Brownian) motion, due to which the fat concentration in the microvolume of the milk emulsion is equalized without applying special means and conditions.

The fat phase of milk is milk fat in the form of fat globules (droplets, particles), the size of which in whole milk ranges from 0.1 to 10 μm.

The majority of fat globules in such milk is 2–6 μm in size, and their average size is 2–4 μm.

The number of fat globules in raw milk is 1.5–3.0 billion in 1 ml.

In the process of homogenization, the average diameter of fat globules decreases to 0.75–1.2 μm, while the number of fat globules increases to 40–80 billion in 1 ml, and the surface area of fat globules increases 13–27 times.

There are no standards and regulations regulating the dispersion degree of milk fat particles after homogenization. The only homogenization standard is GOST 27203-87 "Gomogenizatory dlya moloka. Osnovnyie parametry" (State standard of USSR 27203-87 "Homogenizers for milk. Main parameters"), which regulates only the main technical parameters of plunger homogenizers of the valve type without taking into account the degree of dispersity of milk fat after processing (currently not active).

To determine the sufficient dispersion of the fat phase after homogenization, there are the following guidelines:

– the chemical control instruction, in which it is recommended to check the quality of homogenization by settling the fat for 48 hours or by the centrifugation method, and it is stated that the method of microscopic determination of the size of fat globules is considered the most reliable;

– the average size of fat globules in the most common valve homogenizers, which reaches 0.75–0.80 μm at operating modes aimed at the maximum dispersion degree [1, 3];

– the average size of fat globules after processing in valve homogenizers according to the recommended modes of homogenization (pressure) in technological schemes for the production of drinking milk and cream, which is considered sufficient, is 1.0–1.2 μm [2];

– the lower limit of dispersion of milk fat emulsion after processing in serial but less common types of homogenizers (vacuum, rotary-pulsating, etc.) is 1.0–1.2 μm [3, 4];

– in accordance with the United States Public Health Service, in well-homogenized milk, there is no visible settling of cream within 48 hours;

– the fat content in the top 100 ml of a 250 ml bottle should not differ by more than 10 % from the milk in the rest of the bottle.

Thus, it can be considered that the dispersion of the milk emulsion is high when the average size of the fat globules is 0.75–0.8 μm and less, and sufficient when the average diameter is 1.2 μm.

3.3 Analysis of the dispersion hypotheses of the fat phase of milk

Dispersion consists of two stages: deformation of the fat globule and its disruption. After dispersion, the newly formed fat globule must be stabilized. Otherwise, the process of its coalescence may occur.

The process of deformation and disruption of milk fat globules is difficult to study experimentally (**Table 3.2**).

Table 3.2 The main reasons for the difficulties in obtaining visual data on the disruption of fat globules of milk during homogenization

The main reasons	A possible way to solve the problem
High velocities of movement of fat globules (up to 200 m/s)	High-velocity filming
Microscopic dimensions of fat globules (0.1–5 μm)	Optical or electron microscopy
Low transparency of milk emulsion	Special dyes
There is little difference in the density of milk plasma and milk fat	
The need to place the objective of the optical microscope at a distance of less than 1 mm from the object of study	Performance of the objective as a part of the working body of the homogenizer
The large length of the disruption zones of fat globules relative to their size (3 orders of magnitude larger than the diameter of the fat globule)	Use of pulsed microlasers

The lack of necessary experimental data led to the appearance of many hypotheses of the dispersion mechanism of the fat phase of milk (homogenization), the main ones of which are presented in **Table 3.3**.

Let's consider the essence and reliability of most theories using the example of the most studied valve homogenizers, which have the highest dispersion degree. The disruption of the fat globule in the valve homogenizer occurs in the gap between the valve and the seat of the homogenizing head, the size of which is 0.3–1.5 mm. The milk supply pressure is 10–25 MPa, as a result of which the velocity of milk in the valve gap reaches 150–200 m/s.

Criticism of the hypothesis of the disruption of fat globules by Prof. Baranovsky, which appeared in the 50s of the last century, is presented in many works [5] and is confirmed by the latest data [6]. The essence of the theory is that a fat globule of milk, moving towards the valve gap, with dimensions d at a flow rate υ_0 at a plasma pressure p_0, is pulled out at the entrance to the valve gap, with a height h where its velocity increases significantly to υ_m at a pressure p_1, and then disintegrates under the action of surface tension forces (**Fig. 3.1**).

Table 3.3 **Basic hypotheses of the milk homogenization mechanism**

The essence of the hypothesis	The authors of the hypothesis
The disruption of fat globules under the influence of the longitudinal gradient of the flow velocity at the entrance to the valve gap	M. V. Baranovsky
Disruption under the influence of the transverse gradient of the flow velocity	P. O. Rebinder, H. Wittig
Disruption due to centrifugal force during rotation of a fat globule	V. D. Surkov
Disruption due to Kolmogorov-Khintse turbulence	Kolmogorov-Khintse
Disruption due to cavitation	A. A. McKillop, H. A. Kardashev, A. N. Tkachenko and others
Disruption of microparticles by blowing from the surface of a fat globule during impulse effects on the emulsion	M. M. Oreshyna
Disruption due to low-temperature cavitation homogenization	E. A. Fialkova
Disruption by boiling of microvolumes of emulsion in a vacuum	A. A. Dolynskyi
Disruption due to the velocity difference between the fat globule and the dispersion medium in the jet collision zone	K. O. Samoichuk

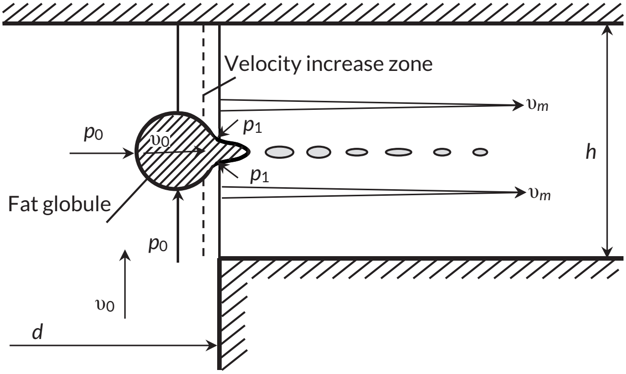

Fig. 3.1 The scheme of homogenization according to the Prof. Baranovsky's theory

The main arguments of the opponents of this theory: the actual scale of the process, where the dimensions of the fat globule are 1–2 orders of magnitude smaller than the size of the valve gap, the impossibility of obtaining a significant difference in velocity over a length comparable to the dimensions of the fat globule (1–3 μm), etc. Calculations of the theoretically possible conditions for crushing a fat globule according to this hypothesis in a valve (the most widespread and studied) homogenizer showed that the necessary pressure drop for the disruption of a fat globule is created only under the condition of entering the valve gap at an angle of 68°, which is unlikely.

H. Wittig proposed to consider the initial fat globule before homogenization as "mother" consisting of several fat particles (**Fig. 3.2**).

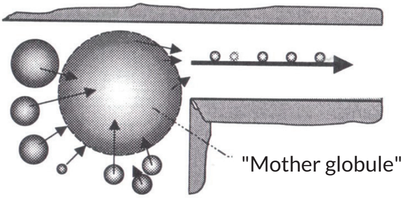

Fig. 3.2 Scheme of the "Mother globule" formation according to Wittig's hypothesis

Thus, the contradiction between the non-observance of the scale between the sizes of the fat globule and the valve gap in Baranovsky's theory was avoided. But, if to agree with this point of view, then the presence of a stagnant zone is necessary, in which the fat globules would merge and form the maternal one. Experiments with the flow of liquid in the gap between the valve and the seat did not confirm the presence of such a zone. In addition, if such a zone existed, the eddy current that would form in this zone would prevent the formation of the mother globule [7].

According to Rebinder's hypothesis (subsequently this theory was also put forward by Wittig) the reason for the deformation and disruption of fat globules of milk is considered to be a large gradient of milk movement velocity in the homogenizing gap of the valve homogenizer. Under the influence of forces acting from the side of the flow, fat globules are stretched into cylinders or threads, overcoming the forces of surface tension and entering an unstable state, and then, under the influence of the same forces of surface tension, they break up into smaller ones. Rebinder established that the disintegration of globules occurs when the ratio of the length of the cylinder to the diameter is equal to or greater than π.

According to the calculations of the conditions created in the valve homogenizer, only half of the fat globules passing through the valve gap can perceive the stretching effect of the velocity gradient (**Fig. 3.3**). The rest of the fat globules pass through the central part of the flow, where the velocity gradient is insufficient for dispersion.

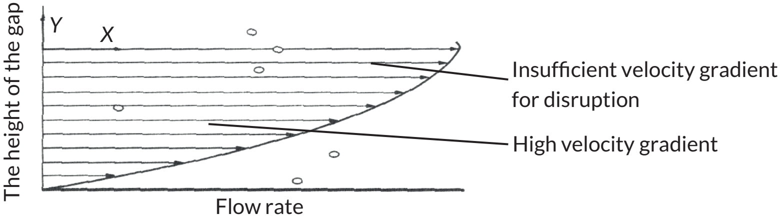

Fig. 3.3 Field of flow velocities in the valve gap of the A1-OG2S homogenizer

Prof. V. D. Surkov suggested that the fat globules should rotate and disintegrate due to centrifugal force in the slit channel. His hypothesis is based on the action of the transverse velocity gradient in the flow, which has different velocities in the cross section. According to this theory, a torque caused by the difference in velocities is applied to the surface of the globule, which is at the boundary of the layers.

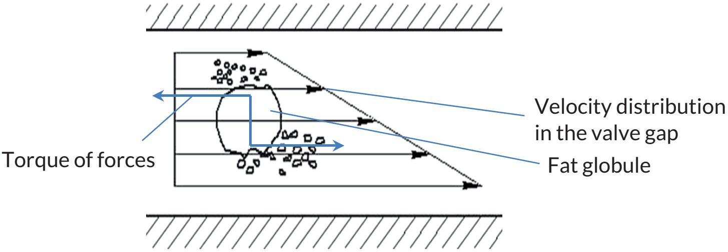

Fig. 3.4 Dispersion of a fat globule according to V. D. Surkov

Under the influence of this moment, each globule, which performs a rotational movement, loses its initial shape, then the centrifugal forces increase, become greater than the forces of surface tension, after which the globule disintegrates into smaller ones. According to this theory, the laminar flow mode in the valve gap is most suitable, which is refuted by experimental studies. Calculations show that half of the fat particles that pass through the central part of the valve gap, where the velocity gradient is small, cannot be destroyed according to the theory of centrifugal disruption.

The hypothesis about the predominant influence of cavitation as the main factor in the homogenization process developed in leaps and bounds: from the main one for valve homogenization to a minor and not influential one [4]. Evidence of cavitation in the valve gap is erosive annular formations on the working surfaces of the seat and valve. But first by M. V. Baranovsky, and later by other researchers, it was experimentally proven that the intensity of cavitation does not affect the homogenization degree, and strongly deformed fat globules pass through the cavitation zone in the initial part of the valve gap intact, and are destroyed much later. Experiments [8] established that the intensity of cavitation in the valve gap is small, in contrast to the exit from the valve gap, where cavitation occurs much more intensively.

Cavitation disintegration, as the main factor of dispersion, develops in two directions: hydrodynamic and acoustic, the mechanism of influence of which on the dispersion of the dispersed phase of the emulsion does not differ.

According to Tkachenko's hypothesis, pulsating cavitation bubbles appear in the cavitation zone and collapse upon contact with droplets of the dispersed phase. Cumulative jets formed in bubbles hit the fat globule and break it into smaller ones.

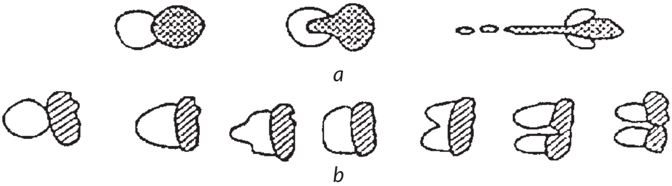

Fig. 3.5 Scheme of the cavitation dispersion process:
a – pulling a fat drop into a bubble; *b* – disruption of a fat droplet of a dispersed phase

According to the principle described above, for the disruption of a fat globule, the coincidence in space and time of at least two factors is necessary:

– the presence of a fat drop in the immediate vicinity of the cavitation bubble;

– the location of the fat drop on the side of the appearance of the cumulative jet.

Such a coincidence of conditions is possible only with a large multiplicity of processing of one volume of emulsion or long-term processing.

Another, and more likely, mechanism of cavitation is the dispersion of the fat phase due to high local pressure differences (shock waves) during the collapse of cavitation bubbles (**Fig. 3.6**).

In the zone of local high pressure around the collapsing cavitation bubble, the pressure reaches 1000 MPa. In addition to hydraulic shock, the temperature rises significantly and hydrogen is released, the presence of which worsens the properties of milk.

The appearance of local high-velocity zones leads to the appearance of high accelerations of microvolumes, which leads to a high velocity of sliding of fat globules relative to the plasma and to their disruption according to the Weber's criterion. In this case, the sliding velocity during cavitation is most affected by the size of the cavitation bubbles and their concentration. It was found [4] that in order to increase the dispersion degree of the fat phase, it is necessary to reduce the size of the cavitation bubbles, which occurs with an increase in the flow rate in the cavitation zone (increase in the Reynolds number), which coincides with the dependence of the dispersion of the fat phase of milk on the flow rate in the valve gap. This may be indirect evidence of disruption due to the sliding velocity of the fat globule.

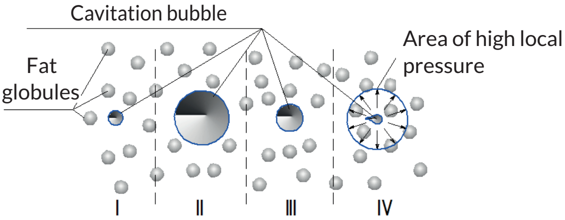

Fig. 3.6 The scheme of the disruption of fat globules during cavitation: I – formation of a cavitation bubble; II – reaching the maximum size of the bubble; III – decrease in size; IV – explosion of the bubble with the formation of a cumulative jet

With cavitation dispersion, the effect of cavitation on the dispersion degree of the emulsion gradually decreases during repeated processing until the moment when dispersion stops due to cavitation. Experiments showed that the minimum size of fat globules due to cavitation reaches only 1.4–2.0 μm. An industrial plant for cavitation milk homogenization will have a low productivity (less than 500–1000 l/h), with an average emulsion dispersion of 2.0 μm and energy consumption much higher than valve machines (20 J/cm^3) at a higher cost of the device.

Thanks to the theory of cavitation, the fact that when cavitation appears, the relation between the homogenization degree and energy consumption changes significantly: with the same supplied energy, homogenization becomes more effective. Homogenization in the valve gap can be organized without cavitation, but this reduces the efficiency of the process.

Taking into account the results of cavitation research, this process can only be an additional intensifying factor for the milk homogenization if it is necessary to obtain highly dispersed emulsions (<1 μm), and the cavitation mechanism of disintegration can be explained by the occurrence of a high sliding velocity during the explosion of cavitation bubbles in milk.

A. N. Kolmogorov and I. O. Khintze presented theories of turbulent dispersion of drops: isotropic and viscous (**Fig. 3.7**).

According to the mechanism of isotropic turbulence, dispersion occurs due to pressure fluctuations caused by microvortices. In the case of a viscous mechanism –

shear stresses of larger-scale vortices. The turbulent homogenization mechanism is the main one compared to the gradient hypotheses of dispersion and cavitation dispersion. According to Kolmogorov's hypothesis, the size of hydraulic vortices determines the dispersion of the emulsion: the smaller the size of the vortices, the smaller the size of fat droplets. And the size of microvortices decreases with increasing flow velocity.

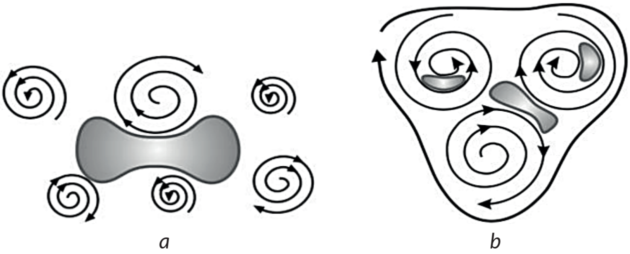

Fig. 3.7 Schematic presentation of turbulent dispersion mechanisms: *a* – isotropic; *b* – viscous

According to the Kolmogorov-Khintse theory, the following can destroy a drop: dynamic pressure and the force of viscous friction. Depending on which of the forces acting on the surface of the drop dominates, two mechanisms of drop disruption are possible. The main factor that determines the dynamic pressure is the velocity of the external medium relative to the droplet (sliding velocity). The average shear rate and specific energy dissipation are decisive for the force of viscous friction. Later, Sleicher proved in visual experiments based on the results of high-velocity photography that:

– the main parameter for the disruption of a fat drop is velocity;

– the Kolmogorov-Khintse theory of isotropic turbulence cannot be used to disrupt droplets in a flow where there is a high velocity gradient;

– the most frequent mechanism of disruption is the pulling out of drops, and when the ratio of their length to the diameter is greater than 4, several new small drops are formed, and when the ratio is less than 4, only two new drops are formed.

Thus, according to the theory of turbulence, it was experimentally proven by visual observations of the disruption of a drop during its extraction according to the viscous mechanism, the main factor of which is the drop velocity. In 2005, these conclusions were confirmed experimentally for the valve gap [8].

The maximum size of droplets formed during crushing in the flow of a continuous medium is determined mainly by three mechanisms:

– Kelvin-Helmholtz instability, which is determined by the value of the relative velocity;

– Rayleigh-Taylor instability determined by the acceleration value;

– the mechanism of disruption by A. N. Kolmogorov's turbulent pulsations, determined by the magnitude of power dissipation.

Therefore, in order to find out the predominant mechanism of the dispersion of the fat phase in the valve gap of the high-pressure homogenizer, thorough studies of the velocity fields of microparticles were carried out using the most modern methods of pulsed lasers [8]. Experiments have shown that cavitation is concentrated in the first half of the valve gap, while the intensity of turbulence in this place is very low. Turbulence is most effective in the exhaust chamber after the valve gap. This confirms the formation in this place of the chamber of turbulent eddies with dimensions comparable to fat globules, which are known to be the most effective for disruption. High turbulence in the last part of the valve gap leads to an increase in the energy of large turbulent eddies and a decrease in the energy of small eddies. This will mean a relative increase in the influence of the turbulent viscous mechanism of disruption in comparison with the turbulent inertial mechanism when dispersity increases. Comparing these findings with the visualization of the dispersion process, turbulence, to a greater extent than cavitation, is the dominant factor in homogenization in the valve gap.

Thus, to date, the predominant effect of the viscous turbulent mechanism of milk homogenization in the valve gap has been experimentally confirmed. Cavitation plays a secondary role, but increases the dispersion efficiency.

E. A. Fialkova puts forward the hypothesis of low-temperature cavitation homogenization or vitrification of fat globules of milk in the process of dispersion, which is based on the idea of the formation of "micro-icicles" on the sub-cavitation surface of cavitation bubbles, formed as a result of sublimation and destroying both the fat globules and the working surface of the valves [9].

According to this theory, in the high-velocity zones of homogenizers, the liquid pressure decreases to such values that sublimation of the surface layer of fat globules occurs due to low temperatures, i.e., their transition into a solid state (**Fig. 3.8**). During further movement, microscopic particles of ice moving at high velocity crush the fat globules.

The author believes that dispersion in the valve homogenizer occurs precisely according to this theory and confirms the pressure distribution in the valve gap experimentally studied by Katsnelson and Mukhin, where the ultra-low pressure zone is shown [9].

The time of presence of a fat globule in the valve gap is only $(1–2)\cdot10^{-5}$ s. The author did not calculate the freezing rate of the surface layer of fat globules in such a short time. Experiments did not confirm the idea of vitrification of fat globules.

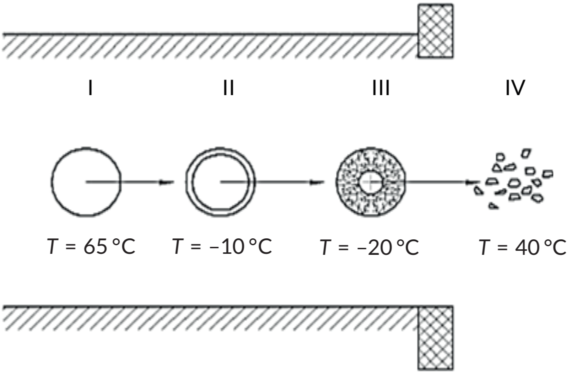

Fig. 3.8 Stages of a fat globule crushing according to Prof. E. A. Fialkova

In the early 2000s, a class of vacuum homogenizers was introduced that was developed on the basis of research by the Institute of Technical Thermal Physics of the National Academy of Sciences of Ukraine. The principle of their operation is in injecting milk heated to 60 °C through a nozzle into a chamber where a vacuum is maintained. The depth of the vacuum is calculated in such a way that the milk drops boil, due to which the fat globules are destroyed. A fundamentally new principle of homogenization provides such advantages as deodorization and reduction of milk acidity. However, in vacuum homogenizers, it was not possible to reduce the average size of milk fat globules to 1.2 μm.

The homogenization theory by boiling microvolumes of emulsion in a vacuum is fundamentally different from other dispersion methods and can only be applied to vacuum homogenizers.

If to compare the theories of M. V. Baranovsky, A. N. Tkachenko, H. Wittig and E. A. Fialkova, the influential factor in all cases will be the velocity of the flow. Indeed, Baranovsky proved that the homogenization degree is affected only by the velocity of the liquid flow. When the flow rate increases through the valve gap, the amount of vacuum will increase and, as a result, cavitation, which is the driving force of homogenization according to the cavitation theory and the theory of Fialkova. At the same time, the velocity gradient increases, which is the cause of disruption according to Rebinder and Wittig. This once again confirms that the factors of the homogenization process and the lack of visual data about it can lead to significant discrepancies and errors in the explanation of its mechanisms and driving forces.

Thus, over the past 60 years, a huge amount of experimental material on homogenization research in valve machines has been accumulated, but it has not yet been possible to directly observe the disruption of fat globules. A breakthrough in this direction was the research of Dr. Frederick Innings at the University of Lund (Sweden). A sapphire window with pulsing lasers along the lumen was created in the homogenizing head, which made it possible to observe the sequence of the fat globule splitting process and photograph it with high-velocity cameras. As a result, it was concluded that fat globules are deformed under the action of acceleration upon entering the gap and pass through it in such a deformed state in an elongated form. Separation occurs only under the influence of turbulent flows, when the globules go outside. It is the velocity gradient – the phenomenon of the difference in velocity of movement of different parts of the stretched globules – that ensures its disruption.

The hypothesis of disrupting a fat globule by blowing microparticles from its surface was put forward by M. M. Oreshyna and then developed by N. A. Palianychka and K. O. Samoichuk [10]. A fat globule is considered like a drop of liquid that is crushed in a high-velocity air stream. The crushing mechanism is based on the breakup of the drop depending on the difference in velocity of the fat globule and its surrounding plasma (sliding velocity), which determines the Weber's criterion (**Fig. 3.9**).

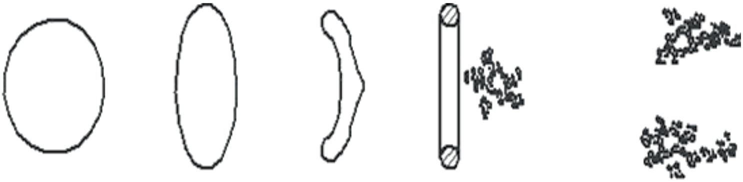

Fig. 3.9 Homogenization scheme according to Prof. M. M. Oreshyna

The mathematical model of the crushing of fat globules by hydraulic disturbances is based on the hypothesis that the dispersion medium captures the fat globule in motion and, taking this into account, the relative movement of the medium and the particle is formed. The significant role of the acceleration of the fat globule was highlighted [11, 12].

The downward or upward movement of the impactor piston causes the dispersion phase to move at a velocity υ_{pl}, which flows around the fat globule moving in the opposite direction due to the inertial force F_i (**Fig. 3.10**) [10].

Experiments on the deformation and disruption of liquid droplets during air flow, carried out in work [9], made it possible to obtain photographs of the disruption and to highlight several characteristics of the disintegration of the globules depending on the Weber's criterion. For M. M. Oreshyna it was possible to obtain photographs of the disruption of an oil droplet in a water flow by pulsed effects, which simulates the characteristics of a fat globule in a plasma flow. According to the author, the size of fat globules of milk after processing in the developed pulse homogenizer is smaller than when processing in valve homogenizers and, on average, is 0.5 μm.

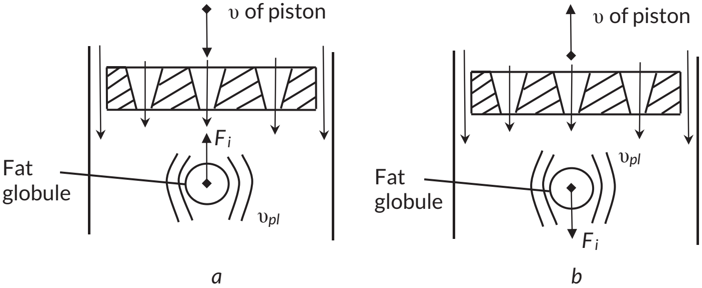

Fig. 3.10 The scheme of the emergence of inertial forces during impulse homogenization during the movement of the impactor piston: *a* – down; *b* – up

The fat globule has a complex structure: milk fat globules are covered with a thin protein-lipid shell, under which is a layer of refractory fats. Such a resilient and at the same time elastic shell creates additional difficulties in crushing the fat globule. In addition, after its disruption, shells are formed again on the surface of new, smaller fat globules, which prevent the process of their agglomeration, which also takes time. If the complex internal structure of the fat globule is neglected, then the view of the process of its crushing will be too simplified and will not correspond to reality. In view of this, a drop of oil in the experiments of M. M. Oreshyna cannot be considered an adequate model of the fat globule of milk.

A small difference between the density of the plasma and the fat globule creates a significant involvement of the movement of the adjacent layers of milk. Therefore, the direct transfer of the mechanisms of liquid grinding in the air stream, where the difference in density differs by almost 3 orders of magnitude, to the grinding of the fat globule in the milk plasma is doubtful. Despite this, the high dispersion degree of the fat phase of milk in the pulse homogenizer allows to conclude that the mechanism of dispersion due to the sliding velocity of the fat globule is promising for further research.

To create the maximum sliding velocity of the fat globule, the homogenization theory during the collision of milk jets was suggested [13]. In the collision zone of the jets, the fat globule, due to the forces of inertia, moves in a straight line with the velocity υ_1 (**Fig. 3.11**), while the velocity of the surrounding plasma υ_2 changes the direction of movement first by 90° and then by 180°. For some time, the fat globule moves in in the counter-jet flow, where the maximum sliding velocity of the fat globule is created, which leads to its disruption in accordance with the Weber's criterion, modified for the case of counter-jet homogenization.

When processed in a counter-jet homogenizer, the sizes of fat globules are comparable or smaller than their sizes during valve homogenization, however, visual observation of the dispersion process was not obtained.

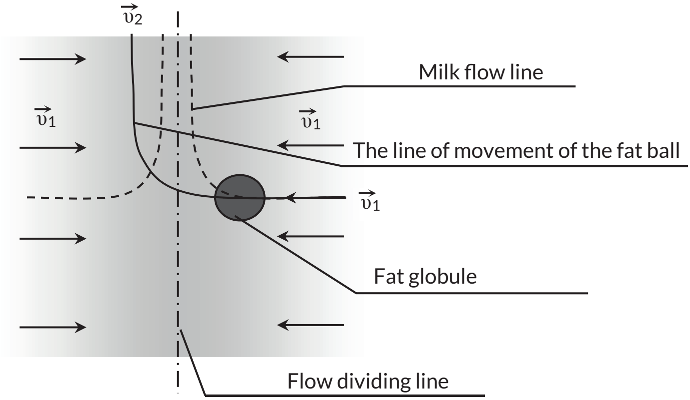

Fig. 3.11 Scheme of homogenization in the collision zone of jets of a counter-jet homogenizer

As a result of the conducted analysis, it is clear that a significant number of homogenization hypotheses are caused by difficulties in obtaining visual data of the disruption of fat globules. Recent studies of the process of dispersion of the fat phase in valve homogenizers indicate a strong stretching of fat globules in the valve gap before disruption and confirm the validity of the turbulent viscosity theory, according to which disruption occurs as a result of Kelvin-Helmholtz and Rayleigh-Taylor destabilization. Such globule disruption mechanisms are caused by the velocity and acceleration of the emulsion flow. Cavitation intensifies the valve homogenization process, but its effect is secondary.

A high degree of dispersity of the fat phase of milk is achieved when using devices built on the hypotheses of blowing the surface of microparticles and the difference in velocity in the collision zone of the jets. The commonality between these hypotheses is the creation of conditions for the occurrence of the maximum velocity difference between milk phases.

Hypotheses of homogenization by boiling microvolumes of emulsion in a vacuum and sub-cavitation homogenization are fundamentally different from others. The first of them did not receive visual confirmation for the valve homogenizer, and the second is applicable only for vacuum homogenizers, the dispersion degree in which does not reach the level of valve machines.

Despite the significant differences of the hypotheses discussed above, they have in common the creation of hydrodynamic conditions in the disruption zone, which contribute to an increase in the relative velocity of the fat globule. For gradient theories, this occurs at the relative velocity of the emulsion layers, for turbulent disruption – at the formation of microvortices, for cavitation – pressure and velocity pulsations in the collapse zone of cavitation bubbles, blowing of microparticles – movement of the emulsion with high acceleration and sliding of the fat globule relative to the plasma due to inertial forces , for the collision of jets – inertial forces during a sudden change in the plasma movement around the fat globule, for sub-cavitation disruption – alternating zones with low pressure and a high velocity gradient.

3.4 Analysis of structural features of homogenizers and generalization of the predominant hydrodynamic factors of dispersion of emulsions

Dozens of devices are used to carry out dispersion processes and obtain emulsions, which are structurally significantly different from each other. Attempts to classify homogenizers used for milk processing are given in works [1, 5, 7, 9], which are based on both structural features and the principle of action together with hydrodynamic conditions in the grinding zone and the mechanism of fat particle disruption. The combination of several features for classification leads to uncertainty, which is exacerbated by the fact that for many types of homogenizers there is no certainty either in the type of the predominant mechanism of dispersion, or in the hydrodynamic conditions in the grinding zone. Classification according to the most defined – constructive signs allows avoiding the above-mentioned contradictions (**Fig. 3.12**).

Slot (valve) homogenizers. The most common in production are valve-type homogenizers, in which the mixture processed under high pressure (from 8 to 25 MPa) passes through a narrow annular gap (0.1–0.5 mm) formed by a valve and a valve seat (**Fig. 3.13**) [1, 7].

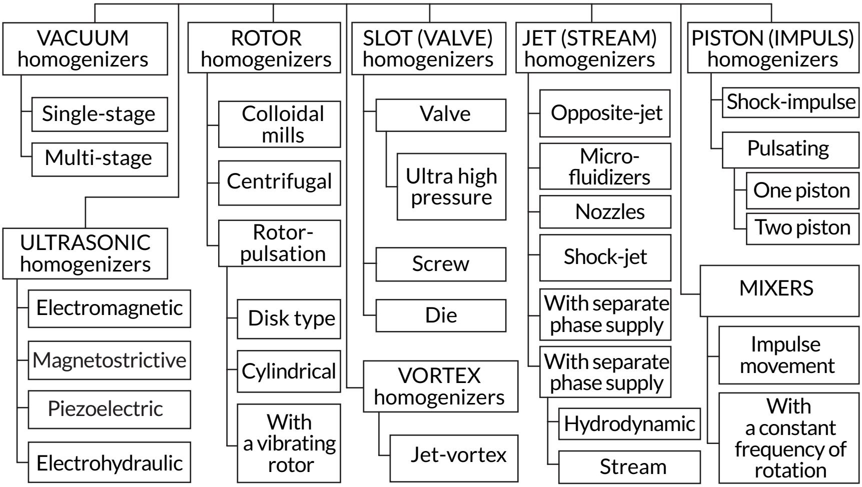

Fig. 3.12 Classification of devices for milk homogenization according to structural features

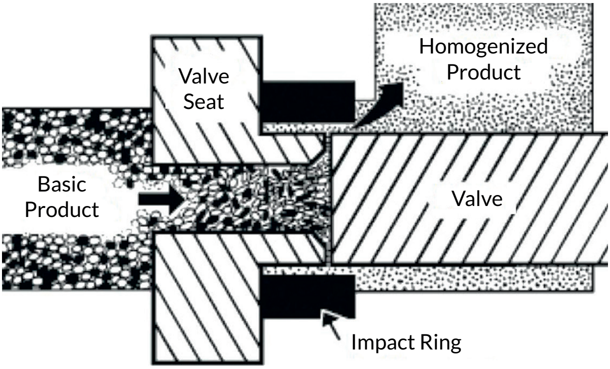

Fig. 3.13 The principle of processing in the valve head of the high-pressure homogenizer

The main advantages of valve homogenizers, due to which they received the highest industrial implementation in the world:

– when processing products, it is possible to obtain highly dispersed emulsions with an average diameter of the dispersed phase of 0.75–0.8 μm;

– insensitivity to obliteration of the working surfaces of the valve and seat due to the "floating" design of the valve;

– versatility, that is, the ability to process milk and cream of different fat content, as well as other products with a wide range of viscosities;

– the vast majority of technological schemes and product production instructions contain recommendations (homogenization modes) developed specifically for valve homogenizers.

Disadvantages of valve homogenizers are significant:

– high cost (more than 120,000 USD at a productivity of 20 t/h);

– the highest, among industrially developed types of machines, energy consumption: 7.4–9 kWh/t, thanks to which the electricity costs for a year of operation reach half the cost of a new machine;

– high mass-dimensional indicators (more than 3 t with a productivity of 10 t/h);

– rapid wear of seals and valves (including cavitation), due to which the cost of maintenance and replacement of worn parts reaches 16,000 EUR/year during milk processing (in the case of homogenization of tomato paste, etc. abrasive products the amount increases significantly);

– the complexity of the design due to the use of a high-pressure plunger pump and high noise level.

Despite numerous improvements of valve homogenizers, the efficiency factor, and therefore the energy efficiency of the homogenization process, remains very low – 0.18 %. At the same time, the mechanical efficiency is quite high (70–85 %), which indicates the imperfection of the homogenization mechanism in valve machines.

Valve homogenizers have the longest history and are characterized by the most research among all other types of dispersers, therefore reliable knowledge of the mechanism of disruption of milk fat globules in this type of homogenizer is key to determining ways to increase the efficiency of homogenization in general. Therefore, let's consider the dispersion process in such a homogenizer in more detail.

The impossibility of observing the milk fat dispersion process led to the emergence of dozens of hypotheses about the possible mechanisms of homogenization in valve homogenizers. Practically each of the hypotheses described in subsection 1.1 was considered the main and predominant one for the valve head of the homogenizer in a certain period of time. But visual experimental data of the process of disruption of fat globules showed that in the valve gap they stretch strongly, pass through the valve gap and break up into small drops at the exit from the working gap.

The obtained results allow to draw the following conclusions:

– visually (stretching into cylinders, with a ratio of length to diameter greater than π), the process coincides with the hypotheses of gradient hypotheses of homogenization;

– hypotheses of disruption due to centrifugal forces (another form of deformation of the fat globule), cavitation, sub-cavitation (which occur only in narrow annular sections of the valve gap) and blowing of microparticles from the surface (according to which deformation in the form of "parachutes" or "umbrellas" is assumed) do not correspond to reality;

– the disintegration of strongly elongated fat globules at the exit from the valve gap occurs due to turbulent pulsations [14, 15], but cavitation increases the efficiency of this process, because in this part of the valve head there is a zone of intense cavitation [4];

– strong stretching of fat globules (formation of long cylinders) before disruption is consistent with the data of Yu. F. Dityakin and M. S. Volynskyi for dispersing highly viscous emulsions in experiments on the disruption of drops and the theory of turbulent viscous dispersion of Kolmogorov-Khintze.

The last conclusion connects the process of dispersing a fat globule of milk with the well-studied process of liquid droplet disruption, which is determined by Weber's criteria and induction time [12]. Weber's criterion is based on the determination of the difference in velocity of the fat globule relative to the surrounding layer (milk plasma). This velocity is called the sliding velocity of the fat globule. The time of induction of the drop dispersion process, as well as the time of its complete disruption, depends on the Laplace criterion, and therefore on the strength of the surface tension of the drop, the drop size and the emulsion velocity. These factors are decisive in the research of valvular homogenization. Of these, the size of the fat globule before homogenization and its surface tension are constant, and the sliding velocity, which mainly depends on the rate of change of the emulsion velocity (or the velocity gradient, or the acceleration of the emulsion) in the valve gap, and the induction time (the influence of dispersion forces) are variable.

Thus, to increase the dispersion degree in the valve homogenizer, it is necessary:

1) increase the gradient (acceleration) of the velocity, for which increase the homogenization pressure and (or) reduce the length (height) of the valve gap;

2) increase the time the fat globule stays in the valve gap, that is, reduce the flow rate and (or) increase the length of the valve gap.

As it is possible to see, these ways of increasing the homogenization degree in the valve head are in contradiction. Perhaps this is the main drawback of this type of homogenizer. Despite more than a hundred years of existence, a huge amount of research and improvements – attempts to reduce its energy consumption without worsening the quality of dispersion, they actually did not succeed. Modern domestic (Odesa Mechanical Plant) and foreign valve homogenizers (Alfa-Laval, "APV", "Bran&Luebbe", Manton-Gaulin, "Cherry-Burrell", Rannie, etc.) have similar technical characteristics and differ mainly only in the degree of automation and technical perfection of their mechanical part.

Ultra-high pressure homogenizers. Industrial and laboratory valve homogenizers have a structure similar to valve homogenizers, operating at ultra-high pressure (UHP) – from 10 to 300 (1000) MPa [4, 16]. The main differences of the UHP homogenization process:

– dispersion of fat globules reaches 0.1 μm and less;

– in the valve head, the temperature rises to 95 °C, due to which milk is disinfected from pathogenic microflora at the same time as homogenization.

Die homogenizers. In such devices, the product is pushed through parallel holes with a constant or variable cross-section. Such devices are the SVA-3 die device and the MDH401 unit (Unitech&Flant-M, Russia-Bulgaria). In these devices, multi-stage processing takes place, which reduces the required pressure compared to valve homogenizers. During the operation of such devices, the efficiency of homogenization is low and is about 17 %, and when processing for 20 minutes – 20 % [17].

Screw homogenizers. Screw devices operate according to the spinner type, in which the screw and the housing form successively located gaps (the ALM unit by Pierre Guerin) [17]. The product passes through a thin screw channel, which significantly increases the processing time. The dispersion degree of milk in screw homogenizers is higher than in die homogenizers.

Rotary-pulsating (rotor-impulse) devices. A typical design of a radial rotor-pulsating device (RPD) is presented in **Fig. 3.14**.

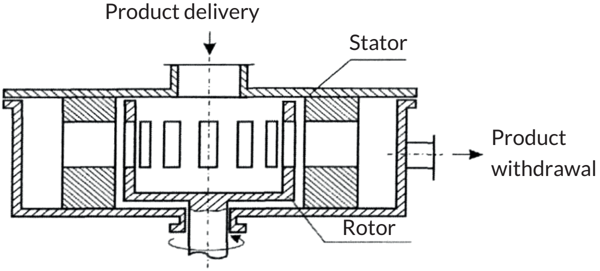

Fig. 3.14 The design of the radial RPD

The working elements of such devices are coaxially arranged cylinders of the rotor and stator, on the side surface of which there are channels for the passage of the processed medium. The part of the RPD, which includes the holes of the rotor and stator, is called the modulator. The principle of RPD operation is as follows [18]. The processed emulsion is introduced into the device through the central nozzle. Passing through the working bodies, the liquid is subjected to significant alternating loads, as a result of which significant shear stresses arise in it. In addition, high-frequency pulsations and cavitation phenomena act on the mixture processed during RPD operation.

When the rotor rotates, its channels periodically overlap or coincide with the stator channels. In the first case, the pressure in the rotor cavity increases, and in the second case, it is reset in a short period of time. As a result, a pulse of excessive pressure spreads through the stator channel, followed by a short-term pulse of reduced ("negative") pressure, since the combination of the rotor and stator channels is complete and the supply of liquid to the stator channel occurs only due to the transit flow from the radial gap between them. The volume of liquid that has entered the stator channel tends to leave it, and inertial forces create tensile stress in the liquid, which causes cavitation. Cavitation bubbles grow under the action of a pulse of reduced pressure and collapse or pulsate when the pressure in the stator channel increases. Part of the cavitation bubbles is carried into the working chamber.

Since the velocity of the liquid flow in the stator channel is high and is also a variable, the flow is turbulent. The working surfaces of the rotor and stator affect the liquid heterogeneous medium due to high shearing and shearing forces arising in the radial gap and turbulent eddies.

Rotary devices refer to devices with periodic transient hydromechanical processes with the excitation of hydrodynamic and acoustic pulsed cavitation and large velocity gradients and significant pulsations. Transient unstable processes are determined by the fact that the period of modulation of the cross-sectional area is shorter than the time of establishment of the main hydrodynamic parameters: velocity and pressure.

Rotary devices are adapted for autonomous operation with or without an external pressure source. In the first case, a product processed by an external pump is fed through the RPD, which is sometimes technologically convenient. In the second case, the pressure is created under the action of centrifugal forces, and to increase the pumping effect, vanes (similar to centrifugal pumps) or a screw-type pre-pump are installed inside the rotor.

According to the method of processing and movement, RPD emulsions are divided into two main types: radial and axial. The radial device is considered above (**Fig. 3.14**), and in the axial devices, the initial components move in the axial direction. Here, the processing of the medium takes place in a narrow gap between the flat discs of stators and rotors with radial slots. The efficiency of such devices is lower than that of radial devices. Radial-type RPDs provide more uniform processing of the medium and are easier to manufacture and operate.

The spectrum of RPD designs, their technological characteristics, and the structure of unsteady flows of processed products are given in works [18]. The peculiarity of unsteady flows in RPD is the variety of their forms (cavitation, non-cavitation, resonant, non-resonant, oscillating, and others), and when designing to maximize cavitation, numerous methods of its excitation are added (acoustic, hydrodynamic, mixed, pulse, resonant, high-frequency, low-frequency, etc.).

RPDs make it possible to intensify technological processes due to carrying them out in non-stationary conditions, using the energy of sound vibrations and secondary acoustic effects, due to the discrete introduction of energy into the processed medium. The devices that most fully meet all of the above requirements include rotary devices with different names:

– rotor apparatus with flow modulation (RAFM);
– rotary-pulsating device (RPD);
– rotor-type pulsating device (RTPD);
– rotor-type hydrodynamic apparatus (RTHDA);
– liquid, hydroacoustic sirens, "Ultraturrax";
– hydromechanical disperser.

These devices are distinguished by their simple design, high reliability and efficiency. They have the same basic design scheme, but the mechanism of action on the processed emulsion of these devices is significantly different, which is related to the size of the radial gap between the rotor and the stator. In rotary devices such as RAFM, RTPD, hydromechanical dispersers, the gap is sought to be minimal – no more than 0.1 mm, while in RPD the indicated gap is more than 0.2 mm and can reach several millimeters. Intensification of dispersion processes in rotorcraft is primarily facilitated by intense pulsed acoustic cavitation [18], high turbulence and a high velocity gradient in working volumes [19].

Most RPD is designed to create advanced cavitation.

Rotary devices are distinguished by the simplicity of their manufacture. Their energy efficiency is due to the fact that the liquid medium is both a source and an object of oscillations and, thus, the mechanical energy of the processed liquid medium is directly transformed into useful energy – necessary for dispersion. Impulse concentration of energy in short periods of time determines their high intensity [19]. The time and frequency of exposure to the emulsion can be adjusted by feeding the product into the RPD.

When studying the dispersion of emulsions processed in RPD, it was established that, in general, the average diameter of the particles of the dispersed phase does not exceed 1 μm [9], but the dispersed composition is uneven and contains an increased number of undisrupted fat globules.

To describe the mechanism of dispersion of emulsions in RPD, three main hypotheses are used: cavitation, turbulence, and gradient. A high velocity gradient ($6.8 \cdot 10^6$ s^{-1})

is created in the gap between the rotor and the stator, which can be compared only with the velocity gradient in the working gap of the valve homogenizer ($8.4 \cdot 10^6$ s^{-1}) [9]. At the same time, high values of the velocity gradient almost uniformly cover the entire volume of the working gap, in contrast to the valve homogenizer. In addition, in the RPD, compared to the valve homogenizer, the time of action of disruption factors increases. But these advantages of RPD did not allow obtaining a dispersion degree comparable to a valve homogenizer. Therefore, the hypothesis of gradient disruption was not experimentally confirmed.

In the 1980s, the prevailing hypothesis of homogenization in RPD was turbulent dispersion. But the authors failed to find experimental confirmation of this theory by visual observation data. In recent times, most RPD researchers use the hypothesis of cavitation disruption as a basic one.

Pulsating devices with a vibrating rotor. A variety of rotor-pulsating devices is a design with a rotor that performs axial oscillations (vibrations) during operation – a pulsating device with a vibrating rotor (PD with VR) [20]. When additional oscillations are imposed due to the vibrating rotor, the energy distribution becomes uniform, and due to the coordination of the rotor oscillations with the overlap of the holes, a resonance of pulsations is created, which additionally increases the efficiency of the process in comparison with the classical RPD. This leads to an increase in the uniformity of the dispersed composition of milk after homogenization and a decrease in the energy consumption of the process. But studies of the operation of such a device were practically not carried out.

Centrifugal rotor homogenizers. In centrifugal homogenizers, under the influence of the rotation of the rotor, liquid under pressure passes through nozzles or slotted holes and hits special reflectors. The disruption of fat globules occurs due to cavitation in cavitation cavities, which are formed behind reflectors [21].

Centrifugal devices are simpler than valve devices, they are less metal-intensive, they do not have fast-wearing plunger pairs. Their main drawback is a low degree of milk homogenization (the average size of fat globules is more than 2 μm) and significant foaming of the product during its processing. Such devices are more often used as mixers, and not as homogenizers.

Colloid mills. Fine dispersion can be carried out in fine grinding mills when the product passes through thin gaps between the working bodies of these machines [22]. But in order to create an emulsion with a dispersion of 1 μm, it is necessary to create developed friction of the working organs of the mill, which contaminates the emulsion with wear products of the surfaces of the working organs and significantly increases the required power of the process. Therefore, colloid mills were not used for milk homogenization.

Vacuum homogenizers. During vacuum homogenization, in addition to dispersing milk fat, such additional advantages are achieved as: reducing acidity, increasing heat resistance, degassing, deodorizing milk, as well as partial inhibition of microflora [23]. The essence of the method is based on the fact that two- or three-fold adiabatic sudden boiling of milk in the chambers leads to crushing of milk fat globules.

In the developed VG-5 vacuum homogenizers, the size distribution of fat globules is comparable to processing in valve devices, but their average size is significantly larger and is 1.5–2.5 μm. The mechanism of milk fat dispersion in vacuum homogenizers differs significantly from other devices in the absence of cavitation. Despite this, when milk drops are boiled in a vacuum chamber, the fat globule enters conditions similar to the hydrodynamic conditions in the zone of high local pressures around the collapsing bubble. That is, intense local pressures act on the fat globule, causing microvortices, which, according to the turbulent theory of disruption, are the cause of the disruption of milk fat globules.

Cavitation devices for dispersion. The principle of operation of cavitation dispersers is based on the use of oscillations from vibration (tens and hundreds of Hz) to the acoustic ultrasonic range (>103 Hz) for the disruption of dispersed phase droplets [24]. Hydromechanical and hydrodynamic generators are used to create oscillations.

According to the principle of operation and construction, cavitation devices are divided into 4 types:

– hydrodynamic (cavitation is generated hydrodynamically as a result of choosing the shape of the working chamber, or by placing cavitating elements in the latter – cavitators);

– hydroacoustic (with and without a resonator) – in which cavitation occurs as a result of pressure pulsations from the vibrations of the acoustic emitter in the ultrasonic frequency spectrum;

– vibrating, in which cavitation occurs as a result of variable pressure due to vibrations caused by external stimuli, such as piezoelectric, magnetostrictive and electrodynamic;

– discharge-impulse, in which a high-voltage discharge in a liquid (electrohydraulic effect) is used, as a result of which electric breakdown in the area surrounding the discharge channel creates high pulse pressures, shock waves and acoustic cavitation.

The intensifying effect of hydrodynamic cavitation is due to the occurrence of a number of effects, namely: pressure pulsations (10^2–10^3 MPa) and rarefaction-compression waves during the pulsation of steam-gas cavitation bubbles; cumulative microcurrents of high energy potential, which destroy phase interfaces; phase transitions on the surface of the bubbles; temperature pulsations (over 10^3 K) due to the collapse of cavitation bubbles.

Cavitation devices are much less energy-intensive than valve devices, compact and easy to maintain, while simultaneously with dispersion and emulsification, the disruption of microflora and cells of microorganisms. Acoustic emulsification makes it possible to obtain dispersion of emulsions starting with a size of 1.2–1.8 μm, which is significantly greater than dispersion after processing in valve homogenizers.

Electrohydraulic homogenizers. Due to extremely high-pressure pulses in the processed product, shock waves are created, which lead to the effect of electro-hydraulic shock. This creates high local pressure and velocity gradients and cavitation, which leads to the dispersion of fat globules to sizes less than 1 μm. But for the uniformity of emulsion processing, it is necessary to significantly increase the processing frequency, which reduces the energy efficiency of the device and worsens the dispersion composition of the emulsion, due to the simultaneous coalescence of fat globules. The taste of the product changes with long-term action of electro-hydraulic influence.

Jet and stream homogenizers. In jet (stream) devices for dispersing the fat phase of milk, homogenization occurs due to the action of a jet (both free and submerged) or a product flow.

The jet homogenizer is a nozzle or nozzle, the jet of which:

– reflected by a closely located reflector (drums);

– immersed in the dispersion liquid of this emulsion (separate homogenization) [25];

– collides with another jet (counter jet) [13];

– exits into a larger chamber, due to which cavitation caverns are created;

– creates hydroacoustic and hydrodynamic cavitation both due to the cavitator, resonator, and due to alternating high and low pressure (cavitation) zones.

OGV nozzle homogenizer was developed by V. Ya. Granovsky. The homogenizing head of this homogenizer consists of two chambers, in the first of which the product is given rotational movement, in the second – translational movement when the liquid passes through the nozzles. Homogenization occurs when the product is injected into the second chamber and when it exits the nozzle. According to the author, the vortex movement of the medium does not play a special role. The main principle of the disruption of fat globules is due to cavitation and turbulence. Therefore, the efficiency of homogenization is 80 % at a pressure of 10 MPa, and the average diameter of fat globules is 1.2 μm, which is 1.5 times larger than in a valve homogenizer.

High sliding velocities are achieved in **counter-jet homogenizers** consisting of two coaxially located nozzles. The dispersion of the fat phase of milk is very high (0.7–0.8 μm) and is comparable to the dispersion achieved in valve homogenizers. Despite low energy consumption and high processing quality, significant foaming prevents the widespread use of such devices [13].

Jet homogenizers that do not have the above-mentioned drawback are homogenizers with separate feeding of the fat phase into the jet of skimmed milk, or skimmed milk into the jet of cream (T-homogenizers) [25, 26]. Such devices make it possible to achieve a high velocity difference between the fat globule and plasma and are not inferior to valve devices in terms of homogenization efficiency. Due to the use of separate homogenization (treatment of only the fat phase), they have low energy consumption (less than 2 kWh/t) [25]. They can also combine the operation of normalizing the milk mixture by fat content, but at the same time, they require preliminary separation of milk into cream and skimmed milk (separation). Due to the need to use thin channels to increase the dispersion degree, counter-jet devices have a high tendency to obliterate the inner surfaces of the nozzles (overgrowth with a product layer). Also, this type of homogenizer makes high demands on the purity of the cream to prevent channel clogging.

Hydrodynamic and hydroacoustic cavitation devices are structures in which cavitation is initiated by alternating zones with different velocities or by interaction of a jet (flow) with a cavitator or resonator. The advantages of hydrodynamic cavitation (decrease of pressure in the flow to values close to the pressure values of saturated water vapor under appropriate conditions) compared to acoustic cavitation are the uniformity of spatial processing of the liquid phase medium and high productivity.

Microfluidizers make it possible to obtain the highest dispersion degree with the sizes of dispersed particles smaller than in the valve UHP homogenizer: 10–100 nm and a narrower range of distribution of fat globules by fractions [27]. The microfluidizer consists of a loading tank, a high-pressure pump (from 100 to 300 MPa) and a working chamber where two (or more) emulsion jets collide at high velocity (more than 400 m/s). During the passage of flows through thin channels (50–300 μm), significant shear stresses (gradient up to 10^7 s^{-1}) arise in the liquid, and during the collision in the shock chamber, high turbulence, cavitation, and high velocities of fat globules flow around.

Microfluidizers allow multiple processing if necessary, but have high specific energy consumption and low productivity (5–50 liters per minute).

Pulsation piston homogenizers. There are devices where the emulsion is formed due to the reciprocating movement of the piston – the so-called pulsating (pulsation) devices [10]. They are usually made in the form of plates or disks with holes, fixed on vertical rods that perform reciprocating movements. The downward or upward movement of the impactor piston causes the dispersion phase to move at a velocity υ_{pl}, which flows around the fat globule moving in the opposite direction due to the inertial force F_i (**Fig. 3.8**).

There are also pulsating devices, which are structurally made in the form of a camera immersed in the device with a system of various nozzles. The dispersion of the emulsion exceeds this indicator for valve homogenization due to the creation of high sliding velocities of the fat globule.

A pulsating homogenizer with two pistons connected by an elastic element showed high efficiency. With the dispersity of the milk emulsion at the level of valve homogenizers, the energy consumption of an industrial model is less than 2 kWh/t.

Impulse impact homogenizers. Dispersion of milk emulsion in pulse homogenizers occurs with piston disturbances with an intensity of 1.5 MPa and a frequency of 50 Hz, created with the help of hydraulic or pneumatic pulse drives [10]. In such homogenizers it is possible to obtain an emulsion with a dispersion that exceeds the parameters of valve homogenizers (0.5 μm), with energy consumption less than 4 kWh/t, which is 2 times less than valve homogenizers. The proposed hypothesis of homogenization in impulse devices (by blowing microparticles from the surface of the fat globule) is questionable due to the complexity of implementing such a disruption mechanism for milk, the density of the dispersed and dispersed phases of which differs by only 5–6 %. But this hypothesis is based on the creation of the sliding velocity according to Weber's criterion, which generally coincides with modern ideas about the homogenization mechanism. The creation of pressure pulses (disturbances) of high intensity is a consequence of the use of a drive with a high braking and acceleration effect, which requires high energy consumption.

High-velocity mixers. Stirrers with a high rotation frequency are universal and widely used equipment for creating stable emulsions of various compositions [17, 28]. They create high velocities of product movement and, unlike valve ones, unlimited time of impact of destructive forces. The variety of constructions of working bodies contributes to the possibility of creating high gradients of emulsion movement. But the mode of operation of mixers is periodic. For uniformity of dispersion during the operation of the stirrer, the product undergoes multiple processing, as a result of which one microvolume of the emulsion is subjected to many "extra" influences of the working bodies, which do not lead to the dispersion of dispersed particles, which significantly reduces the energy efficiency of the process. With constant movement of the stirring organs, despite the high velocity of the emulsion, the velocity gradient decreases, which reduces the dispersion degree. To increase it, it is necessary to use pulse modes of movement of the mixer, which are energy inefficient due to high energy consumption during acceleration and braking. Thus, high-velocity mixers have not been widely used for the preparation of microemulsions, such as homogenized milk, and are most often used as emulsifiers (with the required dispersion of more than 2 μm).

Vortex homogenizers. Vortex homogenizers are designed to create maximum dispersion conditions according to the theory of low-temperature cavitation homogenization, the driving force of which is sublimation [29]. The design of this type of homogenizer is based on the principle of a vortex tube, the theory of which is currently not developed, which, according to the authors, allows obtaining the maximum length of ultra-low pressure zones.

The dispersity of the emulsion after processing in the vortex apparatus reaches 1.2 μm, and the energy consumption is at the level of countercurrent-current 3.8 kWh/t.

The Y9-OGZ brand jet-vortex apparatus is an emulsification block with six holes with a diameter of 5 mm. The productivity of the machine is 8,000 l/h, the working pressure is 0.3–0.4 MPa. The average diameter of fat globules after processing in an emulsor is 1.6–2.2 μm.

Let's analyze the main dispersing factors in modern homogenizers of the dairy industry (**Table 3.4**).

Table 3.4 Predominant hydrodynamic phenomena that lead to the disruption of fat globules of milk in the main types of devices for homogenization

Homogenizer type	Turbulence	Liquid flow gradient	Flow around a fat globule	Cavitation	Electro-hydraulic shock	Sublimation	Boiling in a vacuum
Valve (die, screw)	•	•	•	•			
Microfluidizer	•	•	•	•			
Impulse			•				
Pulsating			•				
Rotary-pulsating	•	•	•	•			
Ultrasound	•		•	•			
Counter-jet		•	•				
Vortex (jet-vortex)			•	•		•	
Jet with separate homogenization			•				
Colloid mills	•	•					
Mixers	•	•	•				
Electrohydraulic				•	•		
Vacuum							•
The main hydrodynamic factors of disruption	Relative velocity of dispersed and dispersive phases and emulsion flow acceleration						

Developers and researchers of homogenizers consider the main causes of dispersion to be turbulence, liquid flow gradient (in longitudinal and transverse directions), flow around a fat globule, and cavitation. Electro-hydraulic shock combines the action of cavitation and hydraulic shock (high flow gradient). But all these factors can be combined with such hydrodynamic factors as the relative velocity of the dispersed and dispersive phases and the acceleration of the emulsion flow. Indeed, both the turbulence, the flow gradient, and the flow around the fat particle lead to the appearance of the fat globule sliding relative to the dispersion medium. This velocity is proportional to the acceleration of the liquid flow. At the same time, the acceleration factor promises to be a more universal indicator for many types of homogenizers, thanks to which it is possible to create designs of highly efficient devices with low energy consumption.

3.5 Generalization of the disruption mechanisms of milk fat globules

Although a huge number of works have been devoted to the issue of breaking up droplets (dispersion, emulsification), the first among which is the study of A. N. Kolmogorov, a sufficiently complete picture of this complex phenomenon does not exist. The most significant results related to this problem were also published in the works of V. G. Levych, R. I. Nigmatulin, H. A. Stone. In apparatuses with stirrers, research was carried out on the crushing of drops in the absence of coalescence, as well as the process of mass transfer from bubbles and drops.

Stone singled out four reasons for the internal movement of a liquid in a droplet: shear flow during a continuous medium; interphase tension; movement caused by droplet buoyancy (i.e. density difference); a change in interfacial tension (Marangoni effect) and/or the presence of surfactants.

Let's try to generalize the possible mechanisms of disrupting fat globules and evaluate the degree of their influence on the final size of particles of the dispersed phase. At the same time, let's consider systems without surface-active substances and with constant interphase tension. The number of such mechanisms reaches ten:

1. Kelvin-Helmholtz instability, arising as a result of a sufficient difference in velocities between the dispersed and dispersive phases.
2. Rayleigh-Taylor instability, which occurs when the force vector is directed from a heavy liquid to a light one (a liquid with a higher density to a lower one).
3. Disrupting droplets in a turbulent liquid flow caused by turbulent pulsations.
4. Tolmin-Schlichting instability, which occurs during the transition from a laminar mode to a turbulent one, when a parallel-jet laminar flow becomes unstable due to the dominance of inertial forces over the forces of viscous friction; can also occur in homogeneous systems.
5. Benardo instability, which occurs due to density fluctuations (when heavy layers of liquid are above light ones), caused in turn by temperature and concentration gradients; can also occur in homogeneous systems.

6. Cavitation mechanism: when a cavitation bubble collapses, due to a local drop in pressure, a stream appears on the surface of the liquid interface, followed by the detachment of one or more drops from it. According to B. G. Novytskyi, this process can also occur due to the transfer of drops of one liquid on the surface of a cavitation bubble during its migration into another liquid (flotation). There is also a hypothesis about the cumulative mechanism of cavitation emulsification.

7. Dynamic – the occurrence of internal dynamic pressure in the drop, caused by toroidal flow or even turbulent movement in it, capable of overcoming external pressure and capillary forces.

8. Crushing of drops near solid walls and other elements of the device.

9. The presence of shear and tensile stresses in a continuous medium capable of significantly deforming a droplet – Couette flow, various types of hyperbolic flows.

10. In case of non-stationary movement of liquids, another droplet crushing mechanism is possible – inertial, experimentally and numerically studied by Stone.

Let's note that most often there is no sharp boundary between the described mechanisms, sometimes some of them can be reduced to others. For example, dynamic and inertial to one degree or another can be considered equivalent.

Let's consider the role of these mechanisms in the disruption of fat globules, for which let's compare the diameters of fat globules of milk in a pulsating resonance apparatus, RPD of cylindrical and disk-cylindrical types (properties of the mediums at a temperature of 60 °C: $\rho_1=923$ kg/m^3, $\rho_2=1030$ kg/m^3, $\mu_1=1.8\cdot10^{-3}$ Pa·s, $\mu=5\cdot10^{-3}$ Pa·s, $\sigma=0.05$ N/m) [30]. RPD properties: the frequency of longitudinal oscillations of the rotor is 50 s^{-1}, the radial velocity in the apparatus is 32 m/s, the maximum velocity in the modulator of the apparatus is 130 m/s.

The analysis results of the globule disruption mechanisms are summarized in **Table 3.5** [18, 20].

Table 3.5 Results of calculating the size of milk fat globules

Dispersion mechanism	Globule disruption mechanisms									
	1	2	3	4	5	6	7	8	9	10
Pulsating resonance apparatus										
d, µm	1.2	1.67	75	–	–	3.6	0.43	8.2	3000	0.68
Cylindrical rotary-pulsating device										
d, µm	0.1–10	0.15–6	0.2–2.5	–	–	4.3	3.8	4.3	94	0.12–6.9
Disk-cylindrical rotor-pulsating apparatus										
d, µm	1–135	1–133	–	–	–	300	–	17–38	28–633	–

Having analyzed the results of the table, it can be concluded that the dominant mechanisms that give the data closest to the experimental ones are Kelvin-Helmholtz, Rayleigh-Taylor, inertial and dynamic instabilities.

In addition to the above reasons for the deformation and crushing of drops in an oscillating liquid, there may also be specific mechanisms associated with the fluctuations of the drop itself.

Rayleigh obtained an expression for calculating the natural frequencies of small oscillations of a liquid drop "near its spherical equilibrium figure":

$$f_n = \frac{1}{2\pi}\sqrt{\frac{8n(n-1)(n+2)\sigma}{[(n+1)\rho_2 + n\rho_1]d^3}}, \tag{3.1}$$

where n – number of oscillations mode; σ – interphase tension, N/m; ρ_1 – density of solid medium, kg/m^3; ρ_2 – density of liquid in a globule, kg/m^3; d – globule diameter, m.

The diameter of the particle that resonates with the oscillation frequency of the emulsion and is crushed into smaller particles:

$$d = \sqrt[3]{\frac{2n(n-1)(n+2)\sigma}{(f_n\pi)^2[(n+1)\rho_2 + n\rho_1]}}. \tag{3.2}$$

The zero mode ($n=0$) corresponds to the radial expansion-compression oscillations of the drop and is impossible for an incompressible liquid, the first mode ($n=1$) corresponds to the translational oscillations of the drop as a whole, which is also impossible for a liquid with constant interphase tension. The results of calculations according to formula (3.2) at $d=2$–5 for the considered system are presented in **Table 3.6**.

Table 3.6 The diameter of the particle that resonates with the oscillation frequency of the emulsion of the self-oscillations of the spherical droplets

f_n, Hz	Globule diameter, μm			
	2	3	4	5
10	5500	7600	9400	11000
100	1200	1600	2000	2400
1000	260	350	440	510
10000	55	76	94	110
500000	4.1	5.6	6.9	81

It follows from **Table 3.6** that a vibration frequency of about 500 kHz is required to disrupt a fat globule with a diameter of 5 μm. Such frequencies are difficult to achieve even in ultrasonic dispersing devices: hydrodynamic whistles, sirens, etc.

Analyzing the application of the above mechanisms for disrupting a fat globule of milk moving in the medium of milk plasma, let's leave in the formulas only variable factors, considering density, viscosity, surface tension and other constants as constants. The results are given in **Table 3.7**.

Table 3.7 Analysis of essential factors for disrupting a fat globule of milk

Dispersion mechanism	Character of dependence of particle diameter on main factors
Kelvin-Helmholtz instability	$d \sim \frac{1}{\upsilon^2}$
Rayleigh-Taylor instability	$d \sim \frac{1}{\sqrt{a}}$
Disrupting drops in a turbulent liquid flow (according to Kolmogorov and Levych)	$d \sim \frac{L^{2/5}}{\upsilon^{6/5}}$
The dynamic mechanism of disrupting drops (according to Levych)	$d \sim \frac{1}{\upsilon^2}$
Sliding mechanism of emulsification (according to Gopal)	$d \sim \frac{1}{\upsilon}$
The inertial mechanism of disrupting drops	$d \sim \frac{1}{\upsilon^2}$

Analyzing the data in the **Table 3.7**, it is possible to understand why most authors use the Weber's criterion to assess the dispersion degree of milk fat [12]:

$$We = \frac{\rho_2 U^2 d}{\sigma}, \text{ or } d \sim \frac{We}{U^2}. \tag{3.3}$$

According to this criterion, the diameter of the globule is inversely proportional to the square of the velocity, which coincides with most dispersal mechanisms, or is close to them. Also, with the data in the table, it is possible to explain why the authors use the velocity of the flow, where the fat globule moves, instead of the sliding velocity of the fat globule (the difference in velocity between the fat globule and the surrounding plasma). This is a simple way, but it does not reflect the essence of the phenomenon at all. The sliding velocity is extremely difficult or impossible to calculate and estimate. Indeed, the velocity of the flow can be as high as desired, but if the fat globule moves together with the dispersion medium, then its sliding velocity is zero, and its disruption does not occur. Dispersion occurs only with a sudden change in the flow, which occurs in valve homogenizers at the moment of passing through a narrow gap and in jet homogenizers when the jets collide. At the same time, the jet change rate will be proportional to the jet rate ($\upsilon \sim U$), which is experimentally confirmed by homogenization experiments in valve and jet homogenizers [5, 7, 31].

3.6 Justification of intensification methods of the dispersing milk emulsion process

To increase the efficiency of homogenization: reducing energy consumption and/or increasing the homogenization degree of milk emulsions is used:

- separate homogenization;
- imposition of mechanical vibrations on the processed emulsion;
- resonance phenomena;
- multiple processing;
- multi-stage homogenization.

3.6.1 Use of separate homogenization

Separate homogenization involves separation of cream from milk by separation and homogenization of only the fat phase (cream) [32]. Homogenized cream is mixed with skim milk after homogenization. This form of homogenization is widely used in the production of pasteurized milk. A significant reduction in the volume of the product to be homogenized proportionally reduces energy consumption by up to 80 % and the required productivity of the machine (approximately 5 times). When processing cream in a valve homogenizer, the required homogenization pressure is reduced by 20–40 % compared to milk.

Some types of homogenizers (jet with separate feeding of the fat phase and T-homogenizers) require mandatory separation of milk before feeding it into the machine. The disadvantage of separate homogenization is the additional costs for separating milk into skimmed milk and cream. There are restrictions on the maximum fat content of cream for processing in a valve homogenizer (18–20 %). In addition, the coalescence degree of fat globules increases, which can lead to a deterioration in the quality of the homogenized emulsion.

3.6.2 Imposition of mechanical vibrations on the processed emulsion

A group of researchers [18–20, 33] studied the effect of low-frequency pulsations on the course of dispersion. The experiments showed that at relatively low frequencies (of the order of tens and hundreds of Hz) and amplitudes of the order of 10^{-3} m, phenomena similar to those occurring in the voiced with the ultrasound liquid are observed, such as vibroturbulation, development and collapse of cavitation bubbles, dispersion of drops, etc., which are of direct interest from the point of view of intensification of the milk homogenization process.

Let's compare two ways of introducing energy into a liquid: in classic homogenizers and when imposing mechanical vibrations. If to consider the power dissipation in such homogenizers as valve, pulsating, rotary, and jet homogenizers, then due to the high unevenness of its distribution over the device volume (in the wall zones of the working organs, the velocity gradient is an order of magnitude higher than in the central ones), the power dissipation does not occur on the surface phase separation, as a result of which energy is used inefficiently. There are well-known cases when, for example, no more than 10 % of particles circulate in an emulsion that is processed three times longer than others, which are "lucky" to more often fall into the zone of action of local pressure gradients and cavitation. Since the entire volume of a heterogeneous liquid vibrates when a vibration is applied, it is logical to assume that dissipation will occur in the entire volume with the same intensity. At the same time, stagnant zones with a low velocity gradient and deficiencies in the dispersed composition of the processed product will be eliminated. Thus, by directing the energy introduced into the device, mainly on the interface of phases, and also in the conditions of resonant oscillations, it is possible to achieve the maximum reduction of energy consumption.

Vibration of working bodies is successfully used in pulse, pulsating and rotary-pulsating devices with a vibrating rotor. As experimental studies show, it is in these types of homogenizers that the highest degree of milk emulsion dispersity is achieved with energy consumption 2–4 times lower than the energy consumption of valve homogenizers.

3.6.3 Use of resonance phenomena

The use of externally controlled vibrational influences to create resonance in mass-energy exchange processes is a known way to significantly intensify dispersion processes [34].

In the mechanics of linear systems without damping (conservative systems), a sharp increase in the amplitude of constant forced oscillations of the system, caused by the proximity of the frequency of external periodic influence on the system and one of the frequencies of its own (non-damping) oscillations, is called the phenomenon of resonance [20]. The peculiarity of these influences is that the frequency of oscillations of the exciting external force corresponds to the frequency of the self-oscillations of the system "apparatus – heterogeneous medium being processed" and is consistent with the maximum mass-energy transfer either in the heterogeneous medium itself or at its boundaries (for example, the walls of the apparatus). At the same time, there are advantages compared to traditional devices, which are associated with a decrease in energy consumption, an increase in relative velocity, volume fraction and a decrease in the size of particles (drops and bubbles).

The features of phase relations during resonance in systems with viscous dissipation (when the friction force is proportional to the velocity of movement) include the vector balance of inertial and elastic forces, between which the reactive component of power is exchanged, and the balance of the vectors of the external (forcing) force and the force in strong friction, and the external force performs work to compensate for losses of active power. Thus, resonance is characterized by the fact that external influences at a steady state of oscillations are needed only to maintain the amplitude of oscillations achieved during the transient process and are spent entirely on compensating for energy losses caused by dissipation in the system. For this reason, the requirement to carry out processes at resonance is taken into account by many researchers when designing pulsating devices.

The analysis of the sizes of drops and bubbles formed in resonant oscillatory apparatus showed that the dominant mechanisms of fragmentation are dynamic, due to high relative oscillating velocities of the phases or their accelerations; the role of turbulent pulsations is secondary [35].

The disadvantage of using resonant modes of operation of the equipment can be an increased mechanical load on the moving parts and units of the device.

In valve, rotary, pulsating and jet homogenizers, the consumed power is dissipated not only on the contact surface of the phases, but also in the entire volume, as a result of which the energy consumption of the device is much greater than the energy required for dispersing fat globules of milk. It is natural to expect that one part of the fat globules will not have time to collapse, and the other will have time to be exposed to destructive forces multiple times. In order to remove to a large extent of the listed drawback, it is necessary to create significant accelerations in mediums with an excellent density of phases.

Let some volume of liquid containing a particle or a globule oscillate. Due to the difference in density, relative periodic slippage of the particle will be observed. Thus, energy dissipation will occur near the phase interface, and all the power supplied to the device will be converted into useful power. Since the entire volume of the heterogeneous medium oscillates, it is logical to assume that with uniform distribution of particles throughout the device volume, dissipation will occur with the same intensity throughout the volume and the forces of interphase interaction will also be the same.

But during the improvement of devices intended for the creation of homogeneous emulsions and dispersions, the creation of conditions for the emergence of resonant vibrational or acoustic oscillations, only in rare cases attention was paid to such an issue as the correspondence of the mode parameters (frequency, amplitude, velocity) of the device to the optimal conditions for homogenization [36]. Thus, the restraining factor in the use of resonant oscillating homogenizers is insufficient study and lack of reliable methods for calculating amplitude-frequency, hydrodynamic and mass transfer characteristics, especially in the resonant mode of oscillations.

Analysis of the design of rotor-pulsating devices with intensification of the process of dispersing the dispersed phase of the emulsion by resonance phenomena. Over the past 20 years, more than 100 patent documents aimed at improving the RPD design have been suggested, and not always the given changes lead to an increase in the efficiency of the process. An analysis of the main design solutions of the RPD, which allow to increase the dispersion degree and/or reduce the specific energy consumption of this process due to resonance effects. Let's dwell in more detail on the most promising, in our opinion, RPD design, in which the rotor, in addition to rotation, performs axial oscillations of a pulsating device with a vibrating rotor. Such RPD (**Fig. 3.15**) consists of a housing 1 in which an electromagnet 10 is mounted.

The rotor 4 is mounted on the shaft 7 and pressed by the spring 8 to the nut 9. The stator 5 is rigidly fixed on the cover 6. There is a minimum gap between the rotor and the stator. The device also includes a cover 11, a seal 12, nozzles 2 for input and 3 for output of components.

The device works like this. The medium processed through the inlet pipe 2 enters the central part of the device and, under the action of centrifugal forces, passes into the gap between the rotor 4 and the stator 5. Due to the impact of the particles on the teeth of the rotor and stator, as well as shear stresses arising in the gap, the particles are being grinded. When an alternating voltage is applied to the coil of the electromagnet 10, axial oscillations of the rotor 4 occur.

The gap increases at the moment of its attraction to the electromagnet. The value of the radial gap is a variable value in time, which allows changing the value of the shear stresses of the heterogeneous medium. In the process of rotor rotation, there is a periodic overlap of the slots, as a result of which a hydraulic shock occurs and the acoustic vibrations are generated. Thus, elastic oscillations and axial vibrations are simultaneously applied to the processed medium. For the device to work effectively, the following condition must be met: the frequency of rotor vibrations is a multiple of the overlapping frequency of the rotor slots. After passing through the active zone, the mixture enters the outer chamber and is discharged through the nozzle 3. Thus, in the suggested design of the RPD due to the electromagnet installed in the body, it is possible to process the medium in resonance conditions, which allows to intensify the technological processes in it and improve the quality of the obtained product.

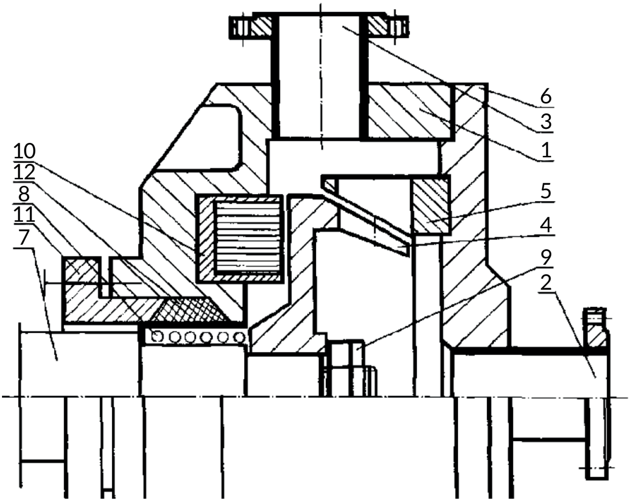

Fig. 3.15 Rotor-pulsating device with a vibrating rotor

Based on the considered structural and technological features of the RPD, the following conclusions can be drawn [37, 38]:

– almost all structural elements are designed to increase the amplitude of pressure pulsations, shear stresses, the development of turbulence and/or cavitation;

– in the existing designs of resonators in the form of needles, membranes and other elastic elements, it is impossible to create modes where the frequency of vibrations and pulsations can be adjusted independently of the rotor rotation frequency. Such possibilities are present only in structures where the rotor oscillates relative to the axis of rotation, which can be controlled independently of the rotation of the rotor;

– for PD with VR, it is noted that the rotor vibration frequency must be a multiple of the overlapping frequency of the holes, which creates conditions for the occurrence of resonance;

– studies of dispersion quality and thorough theoretical studies of RPD with mechanical vibration generators have not been carried out, therefore, the study of such devices is a promising direction of further research, which can increase the efficiency of emulsion homogenization in RPD.

3.6.4 Multi-stage homogenization

Multi-stage homogenization has been established in valve homogenizers. For this purpose, the valve head consists of two independent "valve-seat" sets. The milk successively undergoes the first stage of processing (under pressure through the annular gap formed by the valve and saddle), and then through the second. The main advantage of multi-stage homogenization is a reduction in the size of fat globules and a narrower distribution of their sizes.

The pressure of the second stage (P_2) is lower than the pressure of the first stage (P_1). The best results are obtained when using the pressure of the second stage of $0.2P_1$. The second stage creates a decrease in the pressure drop on the first stage of the valve homogenizer [39]. The mechanism of influence is explained by: changes in the cavitation mode in the valve gap of both stages, changes in turbulence or the disruption of agglomerates of fat globules that formed after passing through the first stage of the valve head.

Two-stage valve homogenizer heads are serially produced, which allow reducing the specific energy consumption of the process by 15–20 % [7]. At the same time, the pressure at the second stage of homogenization is lower than the pressure at the first stage. In addition to valve homogenizers, two-stage homogenization is used in vacuum homogenizers of the GV type.

The mechanism of energy consumption reduction during multi-stage homogenization is explained: firstly, by increasing the exposure time of the hydrodynamic factors of disruption, and secondly, by covering most of the fat globules with its destructive factors.

3.6.5 Multiple processing

Increasing the multiplicity of fat emulsion processing – the number of passes through the working bodies of the homogenizer – is used in many types of homogenizers, such as ultrasonic, pulsating, die, jet, electrohydraulic, and mixers. Multiple passing of the product through the working organs of the device leads to a significant increase in emulsion dispersion (by 2 or more times), in contrast to two-stage homogenization, due to which dispersity increases by a maximum of 20 %.

For mixers, ultrasonic and electro-hydraulic devices, multiple processing is necessary to achieve high dispersion due to the fact that the working bodies in one cycle of passing the emulsion do not provide either complete coverage of the entire volume of the emulsion, or the necessary intensity of impact. Involvement of most of the fat globules under the influence of destructive factors during multiple processing is necessary due to the heterogeneous structure of the flow in the homogenizers. For example, in mixers, the hydrodynamic conditions of the wall layer of the emulsion differ significantly from similar conditions in the central zone, where the flow rate is lower. The velocity gradient in the wall zones is 2–3 times higher than in the central part of the flow [15].

In contrast to the multi-stage homogenization, the hydrodynamic conditions in the working bodies do not change during multiple homogenization.

With multiple processing, the fat particles, which during the first passage through the valve gap got into zones unfavorable for disruption, can avoid such zones during the second (or more) passing. Thus, with an increase in the frequency of processing, the probability of fat globules entering the zones of the working bodies of homogenizers with hydrodynamic conditions sufficient for disruption (high velocity gradient, zones of cavitation micro- and macro-perturbations, zones of high flow acceleration, etc.) increases.

According to experimental data obtained by E. V. Nuzhin [7] for valve homogenization, the dependence of homogenization efficiency on multiplicity (the number of passes through the valve gap of the homogenizing head) is parabolic (**Fig. 3.16**).

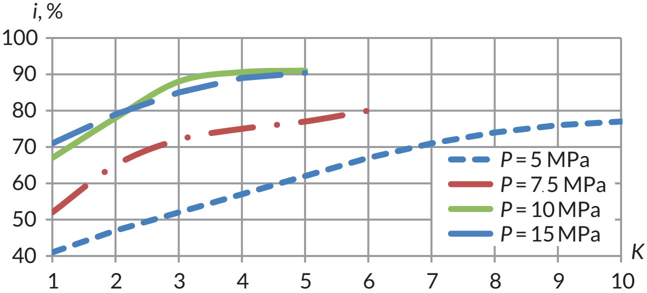

Fig. 3.16 Dependence of the homogenization efficiency (*i*) % on the homogenization pressure (*P*) MPa and the frequency of passing through the valve head *K*

Several conclusions were drawn from these data:

– when developing or improving homogenizers in order to reduce specific energy consumption, it is necessary to try reducing the frequency of passing the product through the working organs of the machine;

– it is possible to reduce the specific energy consumption of the homogenization process due to multiple processing, if at the second (or more) stage, modes with lower energy consumption are used, for example, to reduce the homogenization pressure;

– to reduce the frequency of processing, it is necessary to create the most uniform conditions of hydrodynamic dispersion in the working bodies of homogenizers;

– pressure (and homogenization efficiency) can be represented as a dependence on the acceleration of the emulsion flow in the valve gap.

Conclusions

1. Despite the widespread use of the homogenization process in the dairy industry, there is a lack of standards and regulations that regulate this process. On the basis of literature sources and technological documentation, which regulate the required pressure of the most common valve homogenizers, the dispersity of the milk emulsion, sufficient for existing dairy production technologies, has been determined: 0.75–0.85 μm.

2. It has been determined that due to the complexity of the structure of the fat globule and its shell, the generally accepted approach of considering only the surface tension as the main characteristic of the strength of the fat globule shells is erroneous.

3. A significant number of generally accepted hypotheses and theories of homogenization, which contradict each other, have been noted. The latest scientific data on the process of dispersing the fat phase in valve homogenizers confirm the validity of the turbulent viscosity theory, according to which disruption occurs as a result of Kelvin-Helmholtz and Rayleigh-Taylor destabilization. Common to these mechanisms is the creation of hydrodynamic conditions in the disruption zone, which contribute to an increase in the relative velocity of movement of the dispersed and dispersive phases and acceleration of the emulsion flow.

4. As a result of the generalization of the ideas of the milk emulsion dispersion process of the developers and researchers of homogenizers, the predominant hydrodynamic phenomena that lead to the disruption of fat globules have been established: turbulence, liquid flow gradient (in longitudinal and transverse directions), flow around the fat globule and cavitation. It has been substantiated that the mentioned

phenomena can be combined by such hydrodynamic factors as the relative velocity of the dispersed and dispersive phases and the acceleration of the emulsion flow.

5. The analysis of intensification methods of the dispersing milk emulsion process makes it possible to identify promising directions for increasing the energy efficiency of homogenizers: increasing the acceleration of the emulsion flow when using sign-changing pulsations, imposing mechanical oscillations, creating conditions for the occurrence of resonance phenomena, and optimizing the multiplicity of emulsion processing and the relative velocity of emulsion phases when implementing the method supplying the fat phase of the milk emulsion into the flow of skimmed milk. 3 principle schemes of promising dispersers have been justified to reveal the potential of the selected areas of efficiency improvement: a pulsating device with a vibrating rotor, a jet homogenizer with a separate feed of the fat phase, and a pulsating piston homogenizer.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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