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RESEARCH INTO MILK HOMOGENIZATION IN THE PULSATION MACHINE WITH A VIBRATING ROTOR

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Обґрунтовано вплив основних кінематичних і конструктивних параметрів пульсаційного гомогенізатора з ротором, що вібрує, на середнє прискорення емульсії в отворах переривника. Встановлено залежність середніх розмірів жирових кульок молока від прискорення емульсії в переривнику апарата та частоти обертання й амплітуди вібрації ротора. Визначені дисперсні характеристики молока після гомогенізації

Ключові слова: гомогенізація молока, гомогенізатор, пульсаційний апарат з ротором, що вібрує

Обосновано влияние основных кинематических и конструктивных параметров пульсационного гомогенизатора с вибрирующим ротором на среднее ускорение эмульсии в отверстиях прерывателя. Установлена зависимость средних размеров жировых шариков молока от ускорения эмульсии в прерывателе аппарата и частоты вращения и амплитуды вибрации ротора. Определенные дисперсные характеристики молока после гомогенизации

Ключевые слова: гомогенизация молока, гомогенизатор, пульсационный аппарат с вибрирующим ротором

1. Introduction

Nowadays it is difficult to find a dairy production scheme where homogenization would not be used [1]. Homogenization improves the taste and sensory internals of milk, increases its viscidity and stability, contributes to a better assimilability of the smaller particles of milk fat, etc [2]. Modern machines which are used for milk homogenization often do not meet modern requirements of quality and energy-savings [3]. Valve homogenizers are the most widespread. They are notable for the highest quality rates of dispersion of milk emulsion, but their energy consumption exceeds 7 kW/t [4, 5]. Despite low energy consumption vacuum, ultrasonic and rotor homogenizers do not provide high degree dispersing [6–8]. On the contrary the ultra-high-pressure homogenizers and microfluidizers provide high degree dispersing of the processed emulsion but have superhigh energy consumption [9, 10]. Taking into account stated above and modern tendency to energy saving technologies implementation the actual problem of the dairy industry is to design machines for milk homogenization with quality rates of dispersion of milk emulsion on a level of valve machines but with lower energy consumption.

2. Literature review and problem statement

One of the main problems of homogenizers study is the absence of the unified homogenization theory for milk [1, 3, 4]. Nowadays there are more than 6 homogenization theories and more than 10 droplets breakup mechanisms that underlie these theories [10]. The major cause for uncertainty in the theories of dispersing of milk fat phase is the lack of experimental data on observing milk fat globules breakup [6, 8]. Their microscopic dimension and high flow velocity in the operating units of homogenizers (up to 200 m/s in valve machines [5]) make it hard to visually observe fat particles breakup.

The process of microscopic milk fat globule breakup in the gap of valve homogenizer was observed in the year 2005 for the first time [12]. The author used sapphire windows in the valve seat and pulsating lasers along operating gap. Fat globules in the operating gap had been determined to be stretched into threads that break up into small droplets. This process fits homogenization theory [13] which was already suggested in the middle of the last century. In addition, these visual data conform to in-depth study on droplets breakup in viscous liquids [14].

High-speed camera enabled to receive oil droplets breakup stages at impact effect on disperse medium [15]. It concluded that breakup is caused by tearing off the surface layer of the droplet. Droplet sizes in the experiment were 1–5 mm, and the results were converted according to the microscopic sizes of milk fat globules by the instrumentality of similarity criteria. Still the validity of such criteria for microworld is doubtful.

Thus, the results of visual experiments of fat phase dispersing process correspond with droplets breakup mechanisms that were thoroughly investigated in the study [14]. According to these investigations dispersing occurs on Weber criterion. Design procedure of valve homogenizers is based on determining Weber criterion as well [4]. Determinative for this criterion is squared difference of velocities between dispersed and continuous phases. This difference of velocities for milk is called sliding velocity of a fat globule relative to milk plasma (disperse medium). It is difficult to determine, that is why they tried to substitute it either for stream velocity [16, 4] or stream velocity gradient [16, 17]. When doing so the essence of Weber criterion is substantially distorted and cannot be the universal breakup factor for homogenizers of different types.

All breakup mechanisms, including on Weber criterion, are based on density difference between dispersed and continuous phases. To separate fat globule and make it move with velocity different from surrounding plasma is the main aim of designing high-efficiency homogenizers. One of the methods to solve this problem is to create impact [15], pulsating [18] or vibratory [19] effects on the medium being processed. Sliding velocity of the fat particle is caused by inertia forces as a result of these effects due to density difference of fat globule and milk plasma. Hydraulic process modeling in the valve gap of the homogenizer corroborates breakup theory due to inertia forces too [9, 20, 21]. Measure of inertia forces is liquid flow acceleration. Indeed, difference of speeds between fat globule and plasma occurs when milk emulsion moves with acceleration due to the density difference between milk phases. That is why flow acceleration is suggested to be used as a fundamental factor of milk fat globules breakup. Acceleration is quite easy to calculate and use as a universal criterion for fat phase dispersing in many types of homogenizers.

Among wide variety of constructions of machines for homogenization, rotor-pulsation machines (RPM) differ in high dispersion of milk emulsion and 4–5 times lower energy consumption than in valve homogenizers [22].

The disadvantage of such homogenizers is the presence of large fat fraction in milk, which occurred in the insufficient power affected zone and were not destroyed. The type of RPM, the rotor of which oscillates along the rotation axis does not have this disadvantage [19]. Pulsation machines with a vibrating rotor (PM with VR) are effective due to dissipation of power on the phase interface of dispersive and disperse mediums throughout volume of product and processing in the resonance mode. Thus, energy consumption of homogenization in PM with VR is 15–30 % lower than in RPM [23]. Such machines reach high values of flow acceleration and thus they are very perspective to achieve high degree of milk fat phase dispersing.

During analytical researches the hypothesis that flow acceleration is the fundamental cause for fat globules breakup in PM with VR has been suggested [11]. Acceleration is determinative for droplets breakup in instability mechanism of Rayleigh-Taylor. Diameter of disperse particle depends on milk acceleration when it moves through the channels of the interrupter. Milk flow acceleration causes velocity difference (sliding) of the fat globule relative to milk plasma. This velocity indeed causes fat particle breakup. Thus further investigations are to be done to test the hypothesis about the key role of the emulsion flow acceleration in the dispersing process and determine the main characteristics of homogenization in PM with VR.

3. The aim and tasks of the study

The aim of the study is to define characteristics of milk homogenization process in PM with VR and influence of flow acceleration on the dispersed rates of milk emulsion.

To achieve this aim the following tasks were being solved:

– analytical definition of dependence of milk emulsion acceleration as a main factor of milk fat particles breakup on design and kinematic factors of PM with VR;

– finding dependence of diameter of milk fat particles (fat globules) on acceleration of milk emulsion and design and kinematic factors of PM with VR;

– definition of dispersed rates of milk emulsion after processing in PM with VR.

4. Materials and methods of studying the homogenization of milk in the pulsation homogenizer with a vibrating rotor

In order to carry out theoretical research we used classical dependences of hydraulics and mechanics, theories of discrete-impulse input of energy, vibrations of conservative linear systems. Experimental research was carried out on the laboratory setup of PM with VR (Melitopol city, Ukraine) [24]. The subject of experimental research is cow's milk with fat content 3.2–4.5 %. Sizes of milk fat globules after homogenization were found with the help of optical microscope equipped with a digital camera. Variable factors at making the experimental research were: rotation frequency of the crankshaft ω_k and crankshaft radius r.

More details can be found in the study [24] that include methods of theoretical research, design model, principles of machine operation, methods of experimental research, subject of research, means to define dispersed rates of milk emulsion, design of the experimental setup for milk homogenization in PM with VR, and also with factors selection for carrying out experimental research.

5. Results of research into homogenization of milk in the pulsation homogenizer with a vibrating rotor

As a result of analytical research, we found the equation of square change of the interrupter of PM with VR, velocity of axial movement of rotor and values of velocity pulsation from centrifugal forces. It enabled us to define velocity dependence of the emulsion movement υ_0 through the interrupter of the machine [25]

$$\upsilon_o = \frac{60\ \omega_k rD\ \cos\beta}{\frac{\pi^2 D}{2z}\left(1+\sin(\varphi z-\frac{\pi}{2})\right)+8\pi\delta}+\frac{\pi\omega_p D^2}{4z(l_p+\delta+l_c)}\left\{\frac{\varphi z}{2\pi}\right\}. \qquad (1)$$

where β, φ – rotation angle of the crank shaft and rotor correspondingly, radians; ω_k, ω_p – frequency of rotation of the crank shaft and rotor correspondingly, s^{-1}; D – diameter of rotor, m; r – radius of the crank, m; $\left\{\frac{\varphi z}{2\pi}\right\}$ – fractional part of the number $\frac{\varphi z}{2\pi}$.

The first constituent of this equation determines velocity, caused by the axial vibrations of rotor, and the second one – by centrifugal pressure at the rotation of rotor. When resonance is created the amplitude of pulsations of emulsion in the interrupter increases, thus increasing the efficiency of homogenization. The condition of resonance creation is making equality $\omega_p=\omega_k/z$ or $\varphi=\beta/z$ [26, 27] and phase angle between the rotation of rotor and crank shaft $\beta=3\pi/2$ [27]. Taking into account these conditions, the equation (1) is transformed into the following

$$\upsilon_o=\frac{60\ \omega_k rD\ \cos(\beta-3\pi/2)}{\frac{\pi^2 D}{2z}\left(1+\sin(\beta-\frac{\pi}{2})\right)+8\pi\delta}+\frac{\pi\ \omega_p D^2}{4z(l_p+\delta+l_c)}\left\{\frac{\beta}{2\pi}\right\}. \qquad (2)$$

To find the acceleration a the latter equation has to be differentiated taking into account that $dt=(1/\omega_k)d\beta$, as a result we will have

$$a=\frac{d\upsilon_o}{dt}=$$
$$=\frac{\pi\omega_k^2 D^2}{4z^2(l_p+\delta+l_c)}-$$
$$-\frac{30\omega_k^2 Dr\left[\frac{2K}{\pi}\sin\left(\omega_k t-\frac{3\pi}{2}\right)+\frac{D}{z}\cos\left(\omega_k t-\frac{3\pi}{2}\right)\cos\left(\omega_k t-\frac{\pi}{2}\right)\right]}{K^2}, \qquad (3)$$

where

$$K=\frac{\pi D}{2z}\left(1+\sin(\omega_k t-\frac{\pi}{2})\right)+8\delta$$

is a coefficient which characterizes the change of geometry of the modulator of PM with VR in course of time, m.

Graphically got dependence $a_c=f(t)$ at D=0.15 m, $\omega_k=$ $=300$ s^{-1}, $\omega_p=50$ s^{-1}, r=1 mm, z=6, δ=1 mm, $l_p=0.005$ m, $l_c=$ $=0.01$ mm is shown in Fig. 1.

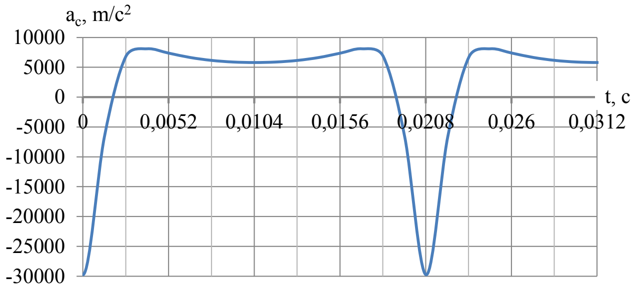

Fig. 1. Dependence of acceleration of liquid a_c in the modulator openings in course of time t

Let`s define the average acceleration a_c for the conditions which correspond to t= 0.0026–0.0182 s (Fig. 1) where the acceleration almost does not change.

$$a_c=\omega_k^2 D^2\left(\frac{\pi}{4z^2(l_p+\delta+l_c)}+\frac{30r}{z\left(\frac{\pi D}{2z}+8\delta\right)^2}\right). \qquad (4)$$

At the beginning and in the end of cycle of closing and opening of the openings the maximal acceleration exceeds the average one more than 3 times, that is why in these periods of time the degree of crushing fat globules considerably exceeds the expected ones by the latter formula.

It is easy to see from the got form (4) that the biggest influence on the acceleration is rendered by frequency of rotation of the crank $a_c\sim\omega_k^2$. Increase of radius of the crank results in the scaling-up of the second element (Fig. 2).

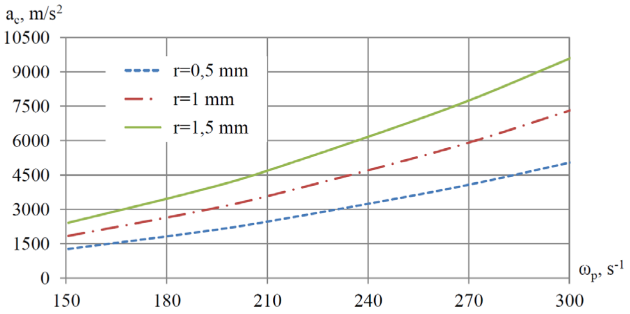

Fig. 2. Influence of frequency of rotation ω_p and radius r of the crank on the average acceleration a_c

The amount of openings z determines frequency of rotation of the rotor ($\omega_p=\omega_k/z$), that is why it substantially influences a_c. Connection between the acceleration and diameter of rotor can be approximately formed as a_c proportional to D (Fig. 3).

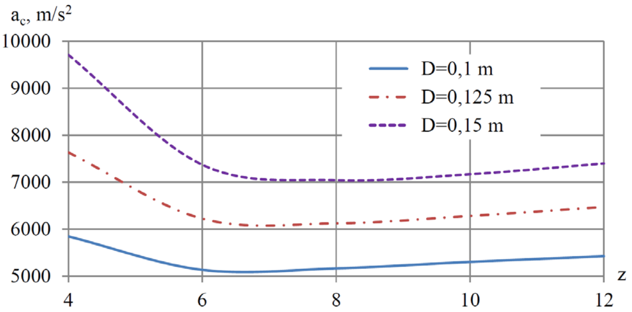

Fig. 3. Influence of amount of openings z and diameter of rotor D on the average acceleration a_c

The charts in Fig. 3 have a minimum, which is on z=6...8. Diminishing the amount of openings to 4 makes the acceleration grow, and the growth rates are as much substantial, as the diameter of rotor is bigger. In the range of z=7...12 it is possible to consider that the acceleration grows linearly at the increase of diameter of rotor.

Thus maximal conditions for crushing fat globules of milk are created at z=4, $(\omega_k, r, D)\to\max$, and $(\delta, l_p, l_c)\to\min$. Variation range of parameters δ, l_p, l_c is small, so their influence on a_c is insignificant.

In the experimental part of research the value of average milk emulsion acceleration a_c was calculated (according to formula (4)) and average size of milk fat globules was defined (Fig. 4) with combination of variable factors (rotation velocity and radius of the crankshaft).

Results with accuracy of 92 % are approximated with form (in Fig. 4 it is shown with a dashed line)

$$d=\frac{68}{\sqrt{a_c}}. \qquad (5)$$

It should be noticed that received dependence is similar to the formula of Rayleigh-Taylor instability for destruction of drops of liquid. It indicates the similarity of mechanism of destruction according to the instability of Rayleigh-Taylor with dispersion of fat globules in PM with VR.

Let's present the results of experiment in the other kind (Fig. 5).

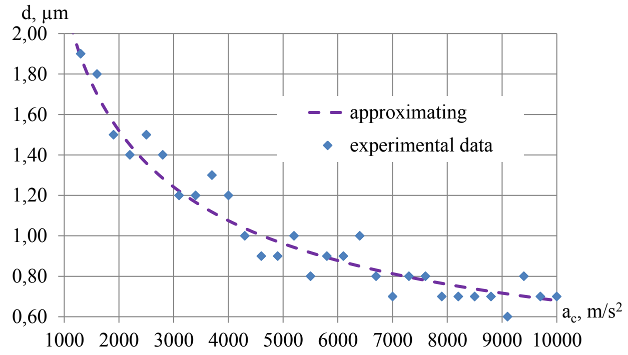

Fig. 4. Dependence between the average diameter of fat globules d after homogenization and acceleration of milk emulsion a_c

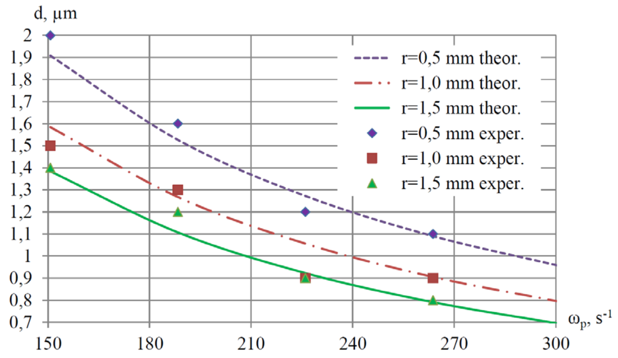

Fig. 5. Dependence of the average size of fat globules of milk d on the frequency of rotation ω_p and radius of the crank r

According to dependences shown in Fig. 5 it is possible to get identical dispersion at different ω_k and r. For example it is possible to get d =0.8 μm when r =1.5 mm and ω_k =260 s^{-1} and when r=1.0 mm and ω_k=300 s^{-1}.

Fractional composition of fat globules after homogenization in PM with VR (at n_k=2880 rpm, r=1 mm) has been compared to the valve homogenization (at pressure 16 MPa). Milk before homogenization is characterized with the following parameters: average diameter of fat globules D=2.6 μm, dispersion σ=1.7, variation coefficient (part of spreading the feature relative to the average) V=68 %. Accordingly we got the following parameters of milk after homogenization in PM with VR and valve homogenizer А1-ОГ2М: D=0.8 μm and 0.9 μm, σ=0.38 and 0.44, V=46 and 49 % correspondingly.

Average diameter of fat globules when processed in PM with VR decreased by 11 % compared with valve, value of dispersion decreased which indicates increasing quality of homogenized emulsion.

6. Discussion of results of research into homogenization of milk in the pulsation machine with a vibrating rotor

The results of the carried out researches are continuation of the study cycle devoted to mathematical model development, design, efficiency determination and features of operation and using PM with VR for homogenization of milk.

Dependence of liquid acceleration in the openings of modulator (Fig. 1) demonstrates surges of acceleration that occur at the moments of opening and closing modulator of PM with VR. According to the current homogenization theory evacuation is created in RPM stator in the very moments of closing rotor openings. It causes milk fat globules breakup due to cavitation [18, 22]. Period of time during which cavitation effects influence considerably (t=0.0182–0.0234 s) makes up only 25 % of the whole cycle duration of closing – opening of the interrupter (t=0.0208 s) for PM with VR. Part of the cavitation effects duration for the rotor-pulsation machine will be similar to PM with VR. Perhaps this is one of the main reasons for milk processed in RPM to have considerable percentage of the large fat particles. Some part of fat globules goes through the openings of the interrupter at the moments of its complete opening and thus is not affected by cavitation and remains unchanged.

For PM with VR BP synchronization of the oscillatory and rotational movements of rotor is made in order to keep acceleration value on the maximal level [27]. In the middle of the cycle when the openings are completely opened (t=0.0104 s) acceleration decreases only by 26 % that indicates much higher uniformity of impact on the fat phase of milk rather than in RPM and allows to forecast high dispersion rates of the emulsion after processing.

Analyzing equations of the average acceleration (4) and graphic dependences of influence ω_p, r, D and z (Fig. 2, 3) minimums on the graph when changing z (Fig. 3) represent the biggest interest. The results show the existence of such values of openings amount (6…10), at which acceleration, and thus homogenization efficiency of PM with VR is minimal. The biggest acceleration can be achieved with the number of openings 4 and less. Plane band of layout of the rotor openings starts to greatly influence determination of acceleration when the number of openings is less than 4. With a large number of openings when the formula (4) was derived the openings of the interrupter of PM with VR were considered flat [25]. But such assumption cannot be already considered valid at z=4 and less.

Design parameters of rotor of PM with VR are closely interconnected. Decreasing amount of openings to provide optimal synchronization of phases results in increasing their diameter and width of the rotor (at unchanged rotor diameter). This makes the emulsion flow through the interrupter. At the same time with unchanged rotation frequency it causes decrease in pulsations frequency and increase in time of the cycle of closing – opening of the interrupter. Application of these factors causes the results shown in Fig. 3.

Interconnection of the average acceleration and average size of the emulsion particles after homogenization in PM with VR is the most important stage of the research that allows to prove or disprove the theory about the determinative influence of the emulsion acceleration in the process of milk homogenization. As we can see (Fig. 4), the validity of approximation of dependence of the fat globules diameter on emulsion acceleration is quite high (92 %). And the character of dependence is similar for instance to dependence of the average diameter of fat globules on pressure for valve [10, 21], jet-stream and pulsation homogenization [7, 17]. In general, increasing influence strength decreases the rates of dispersion growth.

In most mechanisms of droplets dispersing the flow velocity is the main factor of breakup. Velocity is the key factor for valve, jet-stream and pulsation homogenization. Velocity is easy to calculate and define for each definite type of homogenizer. Though the same values of velocity for example for jet-stream and valve homogenization give absolutely different degree of homogenization. Acceleration in this meaning promises to be more universal characteristic for many types of homogenizers. Mechanism of droplets breakup of Rayleigh-Taylor is distinguished by being based on calculation of flow acceleration. We are to find out fundamentally the similarity of dispersing on Rayleigh-Taylor mechanism in the further researches.

As a result of investigation of energy consumption of PM with VR we found operation modes with a minimal r to be optimal [23]. In these operation modes energy consumption is minimal. Thus at r=1.0 mm (that equals amplitude of oscillation 2 mm) specific energy consumption of the process is less. Thus in designing industrial models of PM with VR it is necessary to choose operation modes with the minimal amplitude of rotor vibration as a rational mode of homogenization. It is explained with the fact that increase of amplitude of the axial rotor vibrations makes acceleration grow less substantially than the increase of the rotation frequency [23].

Experimental results of the research into dispersed composition of milk after processing in PM with VR and their comparison with valve (the quality of which is completely satisfying for any processes of the dairy industry [1, 4]) indicate in advantage of processing in PM with VR [29]. Moreover these indexes are reached at specific energy consumption considerably less than in valve homogenizers [23]. The results received prove that PM with VR can substitute existing in the industry valve homogenizers in milk processing with its rates of quality and energy consumption. Future researches are planned to define efficiency of PM with VR for processing viscous products (creams, mixes for producing ice-cream, mayonnaise).

It should be noticed that with stated above advantages design of PM with VR that has a vibrating unit is rather complicated and in this it is almost similar to valve homogenizers which are one of the most complicated and expensive machines for homogenization. Thus decreasing negative influence of vibration is the problem to be solved when designing industrial models of PM with VR.

7. Conclusions

The conducted analytical and experimental researches resulted in:

– determining influence of basic parameters of PM with VR on the index of average acceleration of the processed emulsion that increases acceleration when the diameter, oscillation amplitude and rotor rotation frequency are increased, and length of the rotor channels, stator and gap between them are decreased and amount of openings in rotor, $z \leq 4$;

– ascertainment of empiric dependence between the average diameter of fat globule (0.7–1.9 μm) and average acceleration of emulsion ($(1–10)\cdot 10^3$ m/s^2) in the interrupter of PM with VR, which proves with the accuracy of 92 % that emulsion flow acceleration is the main factor of homogenization in PM with VR;

– determining that at frequencies of rotation of the crank shaft up to 2880 rpm and amplitude of rotor oscillation 1 mm it is possible to get milk emulsion with the average size of around 0.8 μm that can be equal to processing in valve homogenizers (with the pressure 16 MPa) that testifies for the perspective usage of PM with VR in the industrial conditions for homogenization of milk.

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