DOI https://doi.org/10.30525/978-9934-588-47-1.21

IMPULSE MILK HOMOGENISATION

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INTRODUCTION

The process of producing fine dispersed emulsions via homogenization is widespread in many industries[1]. Homogenization has been most widely used in the dairy industry, where it is one of the most important technological processes. Homogenization of fat particles to microscopic sizes increases the nutritional value of milk, improves its sensory and taste properties, increases stability during storage and transportation, etc.[2]. The quality of products using homogenized milk is much higher. That is why homogenization is the normative process in most technological schemes for the production of drinking sterilized and pasteurized milk, fermented milk products, ice cream, canned milk, and cheese production. With the development of technologies, homogeneous components are being applied, and higher requirements for the dispersion of the final product are being made.

The main technical problem of obtaining fine emulsions is the limited capacity of homogenizers. Therefore, designing devices and methods for producing finely dispersed emulsions with the ability to vary dispersion and high productivity is of high relevance.

Valve homogenizers are mainly used for homogenization of milk and dairy products. However, analysis of valve homogenizers design showed that they have significant drawbacks: big overall dimensions and weight, high metal consumption, high energy consumption, rapid wear of the valve surfaces and a fairly high cost of equipment. It should be noted that other existing types of homogenizers either do not allow to achieve such degree of dispersion of the fat phase, or have sufficiently large energy costs for the process. Thus, the issue of improving the existing and

[1] Wilbey R.A. Homogenization of milk. *Encyclopedia of Dairy Sciences,* 2002. P. 1346–1349. doi: 10.1016/ b0-12-227235-8/00202-9.

[2] Michalski, M.-C. Januel C. Does homogenization affect the human health properties of cow's milk? *Trends in Food Science & Technology*. 2006. Vol. 17, Issue 8. P. 423–437. doi: 10.1016/j.tifs.2006.02.004.

creating new devices for homogenization of the fat emulsion remains quite relevant today.

Impulse homogenization can be considered a promising way of dispersing a fat emulsion. A laboratory unit for studying the process of impulse homogenizatio has been developed on the basis of the Department of Equipment of Processing and Food Production named after Professor F. Yalpachyk of Dmytro Motorny Tavria State Agrotechnological University.

1. Theoretical researches of the impulse homogenization process

The main purpose of the study is to reduce energy consumption of the process of dispersion of milk emulsion by using a device for impulse homogenization.

Installation for impulse homogenization consists of a working chamber of the impulse homogenizer 4 (fig. 1) with the percussion piston 5, which are driven into oscillatory motion with the spindle 9 by the actuator 8.

The main percussion piston is tightly fixed on the spindle and the additional piston is connected to the main by a spring. In order control the oscillation frequency of the percussion piston, the direct current motor is used. An adjustable crank is used to change the oscillation amplitude of the percussion piston[3]. At the bottom of the chamber there is a valve for removal of milk after homogenization 6 into the tank 7.

Milk is fed to the working chamber of the homogenizer from the receiving tank 1 by the pump 3. The valve 2 is used to supply the milk under the required pressure to the pump and the working chamber of the homogenizer.

The impulse actuator is used to create oscillating motions of the spindle and the pistons strikers in the working chamber of the homogenizer. This impulse actuator is an adjustable crank mechanism that is coupled to a V-belt with the direct current motor.

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[3] Гвоздєв О.В, Паляничка Н.О., Яворницький В.М. Пошук конструктивного рішення імпульсного гомогенізатора молока. *Праці Таврійського державного агротехнологічного університету*. Мелітополь : ТДАТУ. Вип. 8, Т. 7. 2008. С. 28–32.

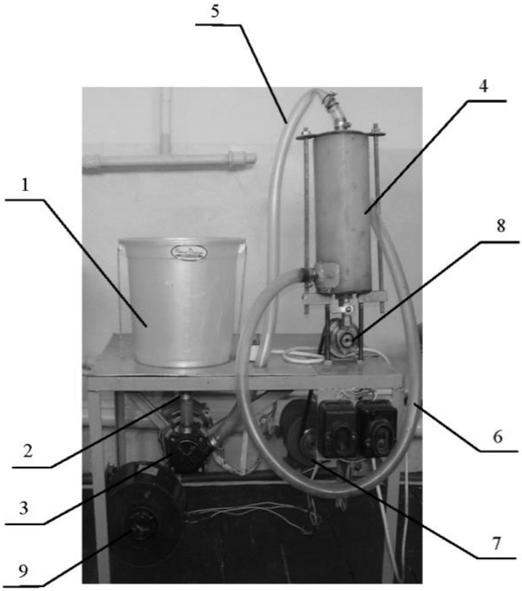

Fig. 1. General type of the device for impulse homogenization of milk: 1 – technological tank; 2 – by-pass valve; 3 – the pump; 4 – working chamber of the homogenizer; 5, 6 – tubes for supplying source and draining homogenized milk; 7 – direct current motor; 8 – impulse drive; 9 – laboratory transformer

As a result of the analysis of forces capable of destroying the fat globule, it was determined that the main force is inertia, which in turn contributes to the appearence of a gradient of the flow rate of milk[4]. In order to intensify the inertia force, the design of a impulse homogenizer with a main and additional percussion piston with through holes, which are connected to each other by a spring, has been suggested[5].

It has been determined that one of the important factors affecting the degree of dispersion is the geometric shape of the openings of the

[4] Паляничка Н.О., Гвоздєв О.В. Аналіз існуючих гіпотез руйнування жирових кульок. *Праці Таврійського державного агротехнологічного університету*. Мелітополь : ТДАТУ. Вип. 10, Т. 3. 2010. С. 48–54.

[5] Giulia Finotello, Roeland F., Kooiman Johan T., Padding Kay, Buist A., Alfred Jongsma, Fredrik Innings, Kuipers J.A.M. The dynamics of milk droplet–droplet collisions. Experiments in Fluids. 2018. P. 1–19.

percussion piston, so that the first necessary condition is to determine the optimal shape and size of these openings.

Openings of cylindrical shape. When the fluid enters the opening due to the inertia forces of the fluid particles, there is a narrowing of its stream. Then, at the outlet of the opening, the jet becomes equal to its diameter.

With this form of the opening, an absolute pressure of less than atmospheric pressure is established in the area of the jet narrowing. This causes the jet velocity at the outlet of the opening to become slower than in the narrowing zone.

At a pressure of more critical value, the absolute pressure at the point of narrowing of the jet in the opening reaches the pressure of vaporization, which promotes cavitation.

In the openings, having the form of a reverse truncated cone and a straight truncated cone, when the jet is narrowed at the outlet of the opening, the vacuum formations are smaller than in the cylindrical holes, so the loss of pressure is lower and the jet velocity in them is greater.

Vacuum voids are not formed in the openings having the conoidal shape, that is, openings made in the form of a compressed jet. Therefore, the feed rate in this case will be maximum, but the jet speed will be slightly less than in the previous case[6].

Among the viewed types of the openings:

– maximum milk feed rate have conoid openings

$$\mu = 0,947 - 0,979\,,\ \varepsilon = 1\,,\ \varphi = 0,947 - 0,979$$ [7];

– maximum flow rate of milk have conical openings, converging with the taper angle 45^{o}

$$\varphi = 0,983\,,\ \varepsilon = 0,875\,,\ \mu = 0,857\,.$$

The carried out analysis showed that the conical shape of the openings with a taper angle of 45^{o} is optimal, which provides maximum jet velocity and maximum productivity.

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[6] Большаков В.А., Константинов Ю.М., Попов В.Н. Справочник по гидравлике. 2–е изд. Київ : Вища шк., 1984. С. 343.

[7] Wilbey, R. A. Homogenization of milk. *Encyclopedia of Dairy Sciences*, 2002. P. 1346–1349. doi: 10.1016/ b0-12-227235-8/00202-9.

The diameter of the openings of the percussion piston is limited by the diameter of the piston and the manufacturability of the openings of the conical shape of the minimal diameter.

As a result of analytical studies for impulse homogenization of milk, it is considered appropriate to characterize the process of grinding the fat phase with a modified Weber criterion, We^i, which is based on the milk flow velocity gradient.

$$We^i = \frac{\rho_{pl} \cdot \left(\frac{dv}{dx}\right) \cdot d_k}{\sigma_{f-p}}, \quad (1)$$

where ρ_{pl} – milk plasma density, kg/m^3; $\frac{dv}{dx}$ – flow velocity gradient, m/s; d_k – critical particle diameter, m; $\sigma_{f\text{-}p}$ – surface tension of the drop, N / m.

When the critical value of the criterion We^i is reached, the fat globules are dirupted. The decisive roll in this case belongs to the velocity gradient.

Since this parameter is difficult to determine, it was decided to calculate the milk flow velocity and the pressure generated during impulse homogenization by computer simulation using the universal Ansys Workbench finite element analysis software[8]. This program has a CFX module that allows you to efficiently and reliably calculate fluid and gas dynamics.

Having the necessary understanding of the model of the working chamber and the geometric parameters of the homogenizer which were calculated previously, with the help of the automation system of design work in three dimensions Solidworks the working model of the camera of the impulse homogenizer had been designed (Fig. 2).

At the beginning of the task, the calculation area was divided into two parts for convenience: the area of milk passing through the openings in the percussion piston and the area of milk passage in the gap between the percussion piston and the cylinder.

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[8] Басов К.А. Ansys: справочник пользователя. Москва : ДМК Пресс, 2005. С. 640.

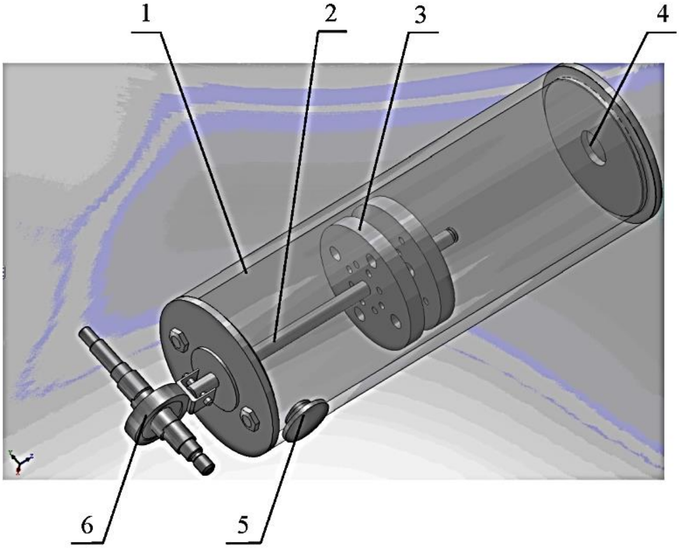

Fig. 2. Model of the impulse homogenizer working chamber is made in Solidworks: 1 – cylinder; 2 – spindle; 3 – percussion pistons; 4 – a branch pipe of supply of initial milk; 5 – branch pipe of draining homogenized milk; 6 – crank mechanism

In the first stage of the calculation, a fixed solution was made by the method of a fixed rotor (Frozen rotor). This allowed a preliminary estimation of the pressure and velocity distribution within the wotking cylinder. In addition, the obtained data showed that it would be most expedient to use the oscillation frequency of the percussion piston 55 Hz[9]. Since, at a smaller amplitude, the flow velocity of milk is very small, that is, it can be assumed that the process of homogenization at this frequency will not occur. And with the increase of the oscillation frequency of the percussion piston, the flow velocity does not increase significantly, and the power at the same time very much increases

[9] Гвоздєв О.В., Самойчук К.О., Паляничка Н.О. Комп'ютерне моделювання імпульсного гомогенізатора молока з використанням програмного забезпечення Ansys Workbench. *Обладнання та технології харчових виробництв: тематичний збірник наукових праць*. Донецьк : ДонНУЕТ. Вип. 28. 2012. С. 294–300.

(by 1.5 times). So in the future it was decided to make calculations at the oscillation frequency of the percussion piston 55 Hz.

An amplitude range of 12 mm was considered to calculate the non-stationary flow of milk. This interval was divided into 6 steps. As a result, the residuals in most equations did not exceed 10^{-5}. Such accuracy is perfectly acceptable for the qualitative assessment of the flow dynamics.

In the impulse homogenizer, the grinding of fat globules occurs due to the formation of a milk velocity gradient dv / dx. Therefore, in order to determine the degree of homogenization, one must first calculate the velocity gradient dv / dx during homogenization[10].

The flow lines of the milk flow velocity distribution depending on the distance x along the length of the working chamber are presented in fig. 3.

According to the obtained data, a graph (fig. 4) of the milk flow velocity versus distance along the length of the working chamber at f = 55 Hz and h = 10 mm was accordingly constructed.

Therefore, as the graph shows, the highest velocity gradient (2.2… 5 m/s) will emerge at the outlet of the conical openings of the second percussion piston. It is logical to assume that the degree of homogenization in this case will be the highest.

At impulse homogenization energy is expended on the force of pressure on the piston and the force of milk supply to the percussion piston[11].

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[10] Deynichenko G., Samoichuk K., Yudina T., Levchenko L., Palianychka N., Verkholantseva V., Dmytrevskyi D., Chervonyi V. Parameter optimization of milk pulsation homogenizer. *Journal of Hygienic Engineering and Design*. 2018. Vol. 24. P. 63–67.

[11] Паляничка Н.О. Визначення шляхів зниження енерговитрат процесу гомогенізації молока. *Вісник Дніпропетровського державного аграрно-економічного університету*. Дніпропетровськ. 2016. №1(39). С. 53–56.

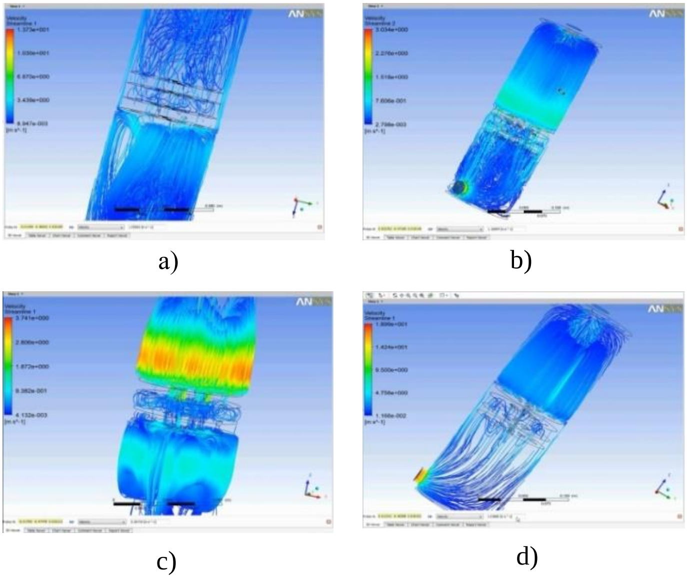

Fig. 3. Three-dimensional graphs of the flow velocity distribution lines of the milk flow in the impulse homogenizer are made in Ansys Workbench: a) at the outlet of the first percussion impactor; b) between the pistons; c) at the outlet of the second piston; d) outside the pistons

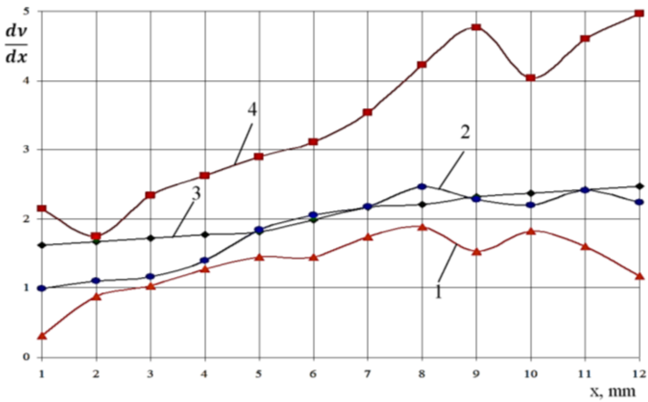

Fig. 4. Graph of dependence of velocity gradients on the length of the working chamber of the impulse homogenizer: 1 – at the exit of the first percussion piston; 2 – between the pistons; 3 – outside the pistons; 4 – at the exit of the second percussion piston

Excluding losses in local supports in the openings of the percussion piston, the power per impulse homogenization process, W, can be represented as

$$P = R \cdot \upsilon , \qquad (2)$$

where R – force of pressure on the piston, H; υ – velocity of movement of the percussion piston (supply), m/s.

The force of pressure on the piston is determined by the formula

$$R = c \cdot \rho_c \frac{\upsilon^2}{2} \cdot S , \qquad (3)$$

where ***c*** – resistance coefficient for circular plate, ***c=1,1 – 1,15***; ***S*** – piston area, ***S*** = 0,061 m^2.

Since in the impulse homogenizer the drive is made with the help of a crank, velocity of movement of the percussion piston (supply) will be determined by the expression [12]

$$\upsilon = \omega \cdot r \cdot \sin\varphi \cdot \left(1 + \lambda \cdot \cos\varphi\right), \qquad (4)$$

where ω - angular velocity, $\omega = \frac{\pi n}{30}$, rad/s; r – crank radius, r =0,070 m; φ – the angle of rotation of the crank; λ – the ratio of the crank radius to the length of the spindle, m.

$$\upsilon = 4,71 \cdot 0,07 \cdot \sin 71^0 \cdot \left(1 + 0,34 \cdot \cos 71^0\right) = 0,35 \text{ m/s.}$$

After the transformations, we get

$$P = c \cdot \rho_c \cdot \frac{\upsilon^3}{2} \cdot S . \qquad (5)$$

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[12] Паляничка Н.О., Гвоздєв О.В., Самойчук К.О. Визначення енерговитрат на процес імпульсної гомогенізації молока. *Тези доповідей Міжнародної науково-практичної конференції ”Состояние, достижения и перспективы переработки, стандартизации и сертификации лубоволокнистых материалов”*. Херсон, 2012. С. 47–48.

$$P = 1,1 \cdot 1029 \cdot \frac{0,35^3}{2} \cdot 0,061 = 1,48 \text{ kW}.$$

The specific energy consumption for impulse homogenization E_s, J / kg, is determined from the expression

$$E_s = \frac{P}{Q}. \qquad (6)$$

$$E_s = \frac{1,48}{1800} = 0.82 \text{ J / kg}.$$

Thus, it can be noted that the specific cost of the impulse homogenization process is 0.82 J/kg, which is much less than in the valve homogenizer (7.4 J/kg).

2. Experimental research on the impulse homogenization process

To confirm the validity of the results of theoretical calculations, the full-factorial experiment was conducted in which the correlation between the degree of homogenization (Y), the amplitude of oscillations of the percussion piston (X_1), the frequency of oscillations (X_2), and the flow of milk into the impulse homogenizer (X_3) had been established.[13]

As a result of the full-scale experiment, the regression equation in coded representation was obtained

$$Y = 4,88 + 0,694X_1 + 0,602X_2 - 0,588X_3 + 0,2X_1X_2 + \\ + 0,426X_1^2 - 0,663X_2^2 - 0,459X_3^2. \qquad (7)$$

To analyze the results of the full-factorial experiment, presented in the form of a regression equation (7), which adequately describes the process of impulse homogenization of milk, a nomographic method was used, which allows to see simultaneously the parameter of optimization of all variables of the independent factors involved in the regression equation, that is how they affect the real technological process.

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[13] Паляничка Н.О., Антонова Г.В. Експериментальні дослідження впливу основних факторів на ступінь гомогенізації в імпульсному гомогенізаторі. *Праці Таврійського державного агротехнологічного університету*. Мелітополь, 2016. Вип. 16, Т. 1. С. 21–28.

Using the Mathcad computer program and the developed methodology, the nomogram (Fig. 5) was constructed to analyze and study the regression equation (7).

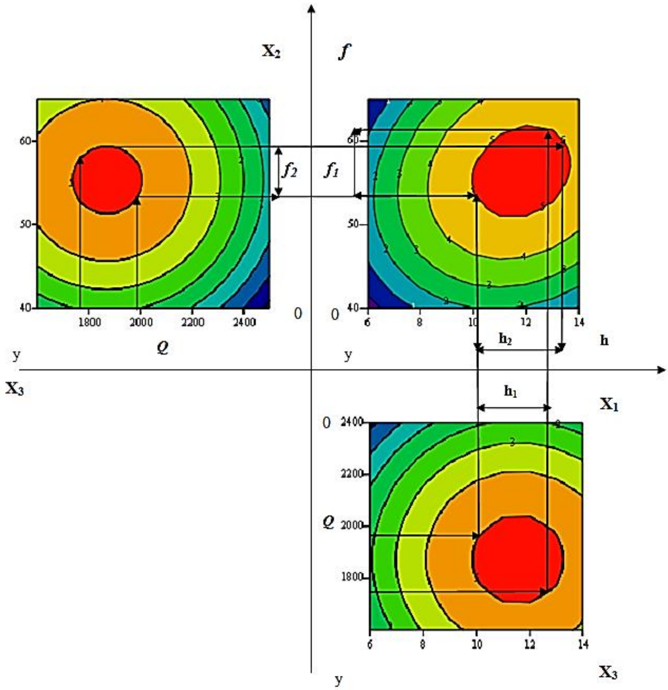

Fig. 5. Nomogram for analysis and determination of optimal parameters of the factors that ensure the degree of homonization of milk in the impulse homogenizer, not lower than 4

Thus, combining the obtained intervals of variation of factors, we obtain that for the impulse homogenizer with milk supply Q = 1800 – 2000 kg/h and the degree of homogenization 5, it is necessary to provide the following technological parameters of the homogenization process: h = 10 – 13 mm and f = 53 – 62 Hz[14].

[14] Важинський С.Е., Щербак Т.І. Методика та організація наукових досліджень : навч. посіб. Суми : СумДПУ імені А.С. Макаренка, 2016. С. 260.

The deviation of the theoretical values of h and f from the experimental parameters in the whole range of parameter changes is within 11%, which confirms the adequacy of the obtained data.

In order to determine the specific energy intensity of the process of homogenization of milk in the impulse homogenizer, the full-factorial experiment was conducted during which the correlation between the energy consumption for the process of impulse homogenization (Y), the amplitude of oscillations of the percussion piston (X_1), the frequency of the oscillations (X_2) and milk supply into the implulse homogenizer was determined[15].

The regression equation is obtained in coded form.

$$Y = 1{,}045 + 0{,}038X_1 + 0{,}032X_2 - 0{,}025X_3 + 0{,}19X_1^2 - \\ - 0{,}2X_2^2 - 0{,}2X_3^2. \quad (8)$$

Using the Mathcad computer program, a nomogram (Fig. 6) was constructed to analyze and study the regression equation (8).

By combining factors variation intervals, it was found that for impulsed homogenizer with milk supply Q = 1800 – 2250 kg/h and h = 10 – 12 mm and f = 43 – 59 Hz, the energy consumption for the homogenization process is 1,5 kW, and the specific energy consumption – 0.83 J/kg.

As a result of the optimum matching of the two nomograms, we can conclude that in order to obtain the maximum degree of homogenization Hm = 5 with minimum specific energy consumption E_s = 0.83 J/kg, it is necessary to create the following conditions: the amplitude of oscillations of the percussion piston h = 10 – 12 mm, the oscillations frequency f = 55 – 59 Hz and milk supply in the impulse homogenizer Q = 1800 – 2000 kg/h.

The deviation of the theoretical values of h and f from the experimental ones in the whole range of parameters change is less than 9%, which proves the adequacy of the obtained data.

To determine the optimal milk temperature for the impulse homogenization process, experimental studies of the dependence of the amplitude of the oscillation of the percussion piston, the frequency of oscillation of the piston, the flow of milk into the impulse homogenizer

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[15] Паляничка Н.О. Експериментальне визначення якості гомогенізації молока в імпульсному гомогенізаторі.*Вісник Харківського національного технічного університету сільського господарства імені Петра Василенка*. Харків, 2016. Вип. 179. С. 39–44.

and the temperature of the degree of homogenization[16] have been carried out. Graphically dependencies are presented in fig. 7, 8 and 9.

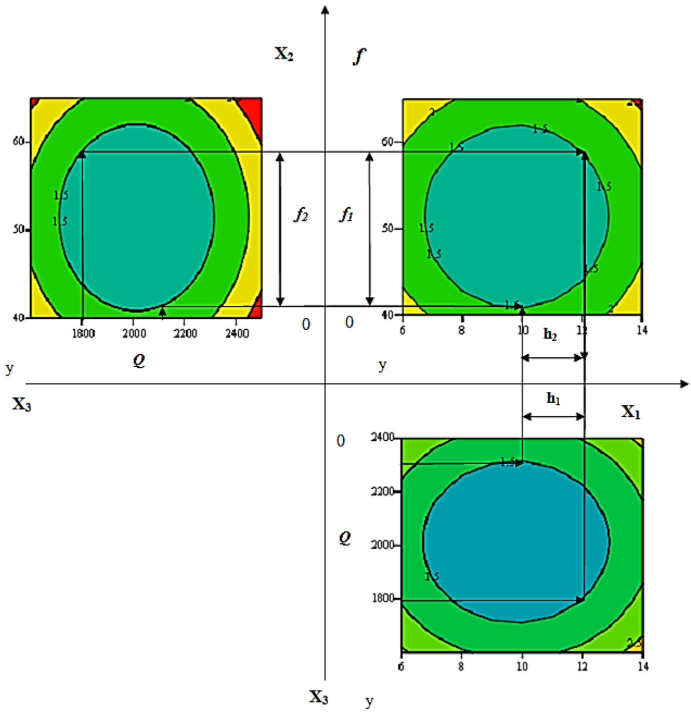

Fig. 6. Nomogram for analysis and determination of optimal parameters of the factors providing the minimum energy consumption for the process of impulse homogenization

During the experiment, it was found that changing oscillation frequency and milk flow in the impulse homogenizer along with the temperature causes linear grow in the degree of homogenization as well.

Analyzing the graphs, we can conclude that the optimal milk temperature for impulse homogenization is 65–70 ºC, since the excess of this temperature will affect the components of milk, in particular the

[16] Самойчук К.О., Ковальов О.О., Івженко А.О. Аналіз методів оцінювання якості гомогенізації молока. *Праці Таврійського державного агротехнологічного університету*. Мелітополь, Вип. 12, Т. 4. 2012. С. 222–229.

stabilization of the fat emulsion, especially since the temperature is most close to production conditions.

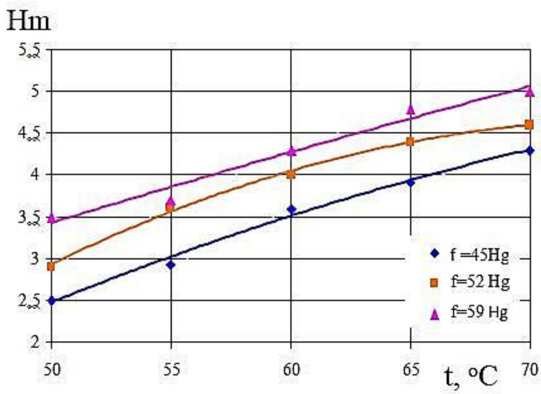

Fig. 7. Dependence of the degree of homogenization on the milk temperature at the frequency of oscillation of the percussion piston f = 45 – 59 Hz, the amplitude of oscillations h = 10 mm and the flow of milk into the pulse homogenizer Q = 1800 – 2200 kg/h

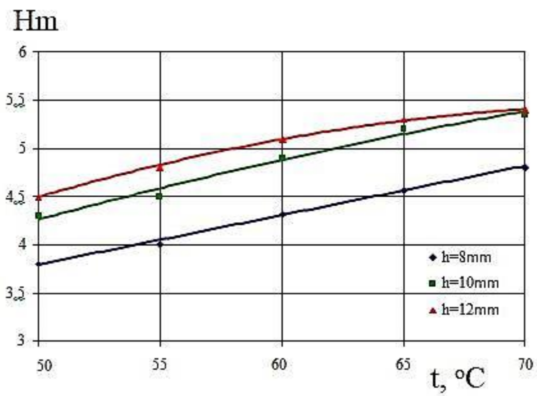

Fig. 8. Dependence of the degree of homogenization on the temperature of milk at the amplitude of oscillations of the piston-impactor h = 8 – 12 mm, the frequency of oscillations f = 55 Hz and the flow of milk into the impulse homogenizer Q = 1800 – 2200 kg/h

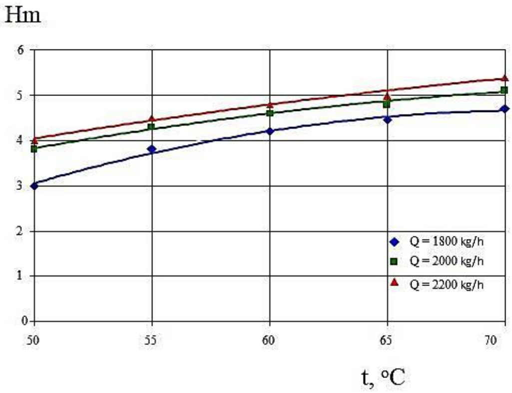

Fig. 9. Dependence of degree of homogenization on milk temperature at milk supply in the impulse homogenizer Q = 1800 – 2200 kg/h, oscillation amplitude h = 10 mm and oscillation frequency f = 55 Hz

The quality of homogenization of milk is determined by the index of milk fat settling χ[17]. Homogenization is considered to be qualitative when, $\chi < 10\%$. Fig. 10 presents the dependence of the index of settling milk fat on the temperature of milk homogenized at h = 10 mm, f = 55 Hz, Q = 1800 kg/h.

Analyzing the graph, we can conclude that at a temperature of milk from 55 to 70°C, the index of settling of milk fat χ <10%. Referring to previous studies, we can assume that the quality of homogenization in the impulse homogenizer is sufficient.

Fig. 11 shows the changes in the fractional composition of fat globules after homogenization in the impulse homogenizer compared to the valve homogenization[18].

Prior to homogenization, milk is characterized with the following parameters: average diameter of fat globules d_a = 2.48 μm, dispersion σ = 1.66, coefficient of variation (dissipation ratio relative to average) V = 67%. After valve homogenization and, respectively, impulse homogenization, these values are: d_a = 0.98 μm and 0.80 μm, σ = 0.50 and 0.46, V = 51 and 56%[19].

[17] Шмойлова Р.А. Теория статистики. 4–е изд. Москва : Финансы и статистика, 2004. 655 с.

[18] Сидоренко В.К., Хайруддінов М.А., Абдулгазис У.А. Основи наукових досліджень : навч. посібник. Сімферополь : СОКАТ, 2000. С. 168.

[19] Drankhar P. Homogenization fundamentals. *IOSR Journal of Engineering.* 2014. Vol. 4. Iss. P. 5–8.

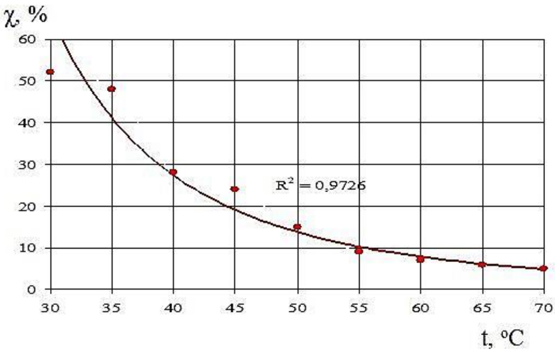

Fig. 10. Dependence of the indicator of the milk fat settling on the temperature of homogenization in the impulse homogenizer

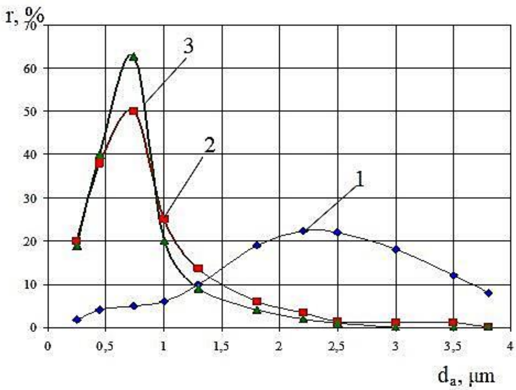

Fig. 11. Differential distribution of fat globules by size: 1 – unprocessed milk; 2 – after homogenization in the valve homogenizer at a pressure of 16 MPa and t = 65 °C; 3 – after homogenization in the impulse homogenizer at a pressure of 1.5 MPa and t = 65°C

The average diameter of the fat globules during impulse homogenizer treatment decreased by 19% compared to the valve, also the value of the dispersion decreased, which in turn indicates that the selected parameters and modes of impulse homogenization provide stability of the fat phase of milk after homogenization.

CONCLUSIONS

Designing new devices for the homogenization of fat emulsions that can provide a sufficient degree of dispersion at low energy costs for the process is quite relevant. The purpose of the conducted researches was to reduce energy consumption for the process of homogenization of milk by applying the process of impulse homogenization and optimization of technological and design parameters and modes of operation of the impulse homogenizer of milk.

As a result of the researches the following conclusions were made:

1. The analysis of the process of homogenization of milk has made it possible to establish that a high degree of homogenization can be achieved if the conditions for the appearance of a gradient of the flow velocity of milk, which leads to the grinding of fat globules, are created. These conditions in the impulse homogenizer are created by the intensification of the oscillation of the percussion piston, with the energy costs for the process of homogenization are significantly reduced.

2. The highest milk flow velocity gradient was found to emerge at the outlet of the conical openings of the second percussion piston. This, in turn, helps to create the conditions for the highest quality homogenization compared to the existing homogenizers.

3. Using the universal finite element analysis system Ansys Workbench it was determined that in order to obtain the maximum flow velocity gradient (2.2 – 5 m/s), it is necessary to create the following parameters of the impulse homogenizer: the amplitude of oscillations of the percussion piston 10 – 12 mm ; oscillation frequency of the percussion piston 55 – 59 Hz; milk supply 1800 – 2000 kg/h.

4. Conducted full-factorial experiment allowed to proove the validity of theoretical studies. It has been determined that the specific energy consumption for the process of impulse homogenization is determined mainly by the amplitude of oscillation of the percussion piston, the frequency of oscillation and milk supply in the impulse homogenizer and are at least 0.83 J/kg, which is 7 times less than the valve homogenizer. It was also found that the optimum temperature of the dispersion process in the impulse homogenizer is 65 – 70 ºC.

SUMMARY

The process of dispersing milk fat is the most energy-consuming process in the technological scheme of production of drinking milk and dairy products. The equipment used is not only high energy consuming but also quite expensive and energy intensive. Therefore, the current

issue remains to be the improvement of existing or designing new devices for the dispersion of fat emulsions, which will be able to provide high quality of the finished product at low energy costs for the process. It is possible to significantly reduce energy costs for the process of dispersing milk fat with a high degree of homogenization by using impulse homogenization. Conducted theoretical and experimental studies have shown that the use of the impulse homogenizer allows to obtain a high degree of homogenization (4–5), with the specific energy consumption for the process of 0.83 J/kg.

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