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METHOD OF CALCULATION OF AN INDUSTRIAL MODEL OF JET-SLOT MILK HOMOGENIZER

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Abstract

Improving the energy efficiency of the dairy dispersion process is an urgent task as more than 8 kW/h of electricity is consumed per ton of the product. The results of prospective studies suggest that a significant reduction in energy costs for homogenization can be achieved through the development and implementation of structures, the principle of which is based on the maximum difference between the velocities of the dispersion (skim milk) and the dispersed (cream) phases of the product. An example of such a design is a jet-slot homogenizer of milk, the energy costs of which, according to the results of analytical and experimental studies, are 5-7 times lower than the most common in the industry designs of valve dispersants. To implement the developed structures and practical implementation of the obtained results in the conditions of real production, it is necessary to develop a method of calculation of an industrial model of jet-slot homogenizer of milk. In order to achieve this goal, the article presents initial data for the calculation of the basic design, hydraulic, technological parameters of an industrial model jet-slot homogenizer in their relation to the average diameter of the fat globules after dispersion, the power of the drives of the pumps and the specific energy consumption. Among the parameters that are determined by the sequence of calculation are the productivity of skim milk and cream, the velocity of skim milk, the diameter of the chamber at the place of maximum constriction, the velocity of cream, the excess pressure of the supply pumps of the dispersion and dispersed phase, the power of the pumps and the specific energy consumption. The article provides information on selected pumps, electric motors, and gears used to supply skim milk and cream. The basic design parameters of the equipment for productivity of 1000, 2500, 5000 and 10000 kg/h are calculated. The obtained results will allow developing an industrial model, to draw up technical documentation and to submit it to the manufacturer for introduction into technological processes of milk processing and calculation on the basis of the obtained data of economic efficiency of implementation of an industrial model of a jet-slot homogenizer of milk with separate supplying of cream.

Key words:
milk, homogenization, calculation, jet-slot homogenizer, productivity, energy efficiency.

Introduction

Dispersion is widely used in the dairyindustry to produce homogeneous emulsions. During this process, the average diameter of fat globules in milk decreases from initial 3–4 μm to 0.8–1.2 μm, which is due to the technological requirements of production (Fialkova, 2006). The operation is carried out as part of most technological processes for processing dairy products to increase the shelf life, increase the nutritional value of products, reduce the loss of milk fat with packaging (Walstra *et al.* 2006). At the same time, the characteristic feature of homogenization is the excessively high values of energy consumption, which for the most common valve machines in the industry is more than 8 kW·h / t of the finished product, which in terms of energy consumption is close to the specific energy consumption of the process of grain crushing in hammer crushers (9–16 kW · h / t) (Fialkova, 2006; Samoichuk, 2018).

Studies aimed at increasing the energy efficiency of the homogenization process are complicated by the lack of a general theory that would comprehensively explain the nature of the processes occurring in the valve gap (Oreshina, 2001). This is due to the microscopic size of the test particles, the average diameter of which is less than 1 micron and the high fluid velocity which exceeds 100 m/s. We know about 7 hypotheses of the dispersion process, on the basis of which more than 10 designs of homogenizers are created, each of which either has high energy costs or does not provide technologically determined quality of the final product (Samoichuk, 2018).

Formulation of problem

Prospective studies by leading scientists show that a significant reduction in energy costs while maintaining the average diameter of fat globules at the level of technologically determined requirements is possible by implementing structures whose principle of action is based on making the maximum difference between the velocities of the dispersion and disperse phases of the product (Samoichuk, 2018). One such design is a jet-slot homogenizer of milk with separates cream supplying, a laboratory sample of which was developed on the basis of the Department of Equipment of Processing and Food Production named after Professor F. Yu. Yalpachik (Dmytro Motornyi Tavria State Agrotechnological University) (Samoichuk, 2019a; Samoichuk, 2019b).

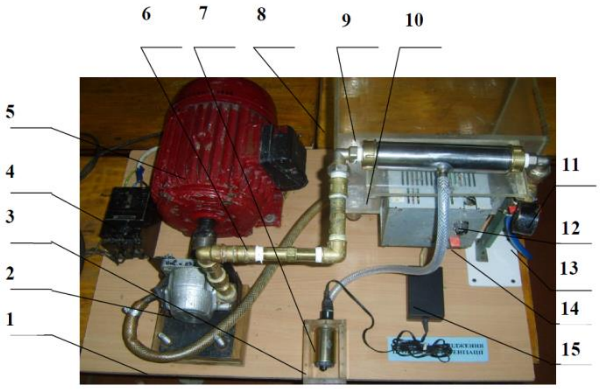

Figure 1. Laboratory equipment of jet-slot homogenizer of milk: 1 – flexible pipeline for supplying skim milk; 2 – gear pump; 3 – container with cream; 4 – packet switch; 5 – electric three-phase motor; 6 – pipeline; 7 – pump for supply of the dispersed phase; 8 – container with skim milk; 9 – homogenization chamber; 10 – flexible hose with a lock for supplying cream; 11 – manometer; 12 – frequency converter with regulator; 13 – flexible hose for draining homogenized milk; 14 – toggle switch for starting the pump for supplying the cream; 15 – electric drive of the pump for supplying cream.

Laboratory installation of milk homogenizer of jet-slot type, the appearance of which is shown in Fig. 1 consists of a container with skim milk 8, from which the product goes through a flexible hose 1 to pump 2 type НШ, which is actuated by an electric three-phase motor 5, which begins to operate when the packet switch 4 is turned. Operating pressure of skimmed milk supply is regulated by the overlap of the draw-selective latch and is controlled by the manometer 11 next to it.

The skim milk from the pump 2 is fed through the pipeline 6 to the homogenization chamber 9, where the dispersed phase is added through the flexible hose 10, in the place of the largest constriction to it from the container with cream 3 by means of the pump 7. The cream supply pump is actuated when the power source 15 is switched on and the toggle switch 14 is started, with the required volume of cream being provided by means of a frequency converter with the dairy industry regulator 12. Normalized and homogeneous milk is discharged through the flexible hose 13 into the special container (Samoichuk, 2019b).

Analytical and experimental studies of the process of dispersion in a jet-slot homogenizer of slot-type milk allow to state that at an average diameter of fat globules of 0.8 microns, energy costs for ensuring the operation of the machine are 0.7 –0.75 kW· h / t of homogenized milk (Samoichuk, 2019a).

Purpose of research

For practical realization of the obtained results and introduction of the jet-slot disperser into the production it is necessary to develop methods for calculating the industrial design of the homogenizer. Therefore, the purpose of this article is to develop and present a sequence of calculations for the practical implementation of the developed homogenizer in production. Analytical dependencies and results of experimental research processing were used to create a calculation method for an industrial sample of a jet-gap homogenizer of milk with separate cream supplying. To achieve this goal several tasks were solved, in particular:

– the initial technological data for the development of the industrial design of the jet-slot dispersant were determined;

– selection of equipment was performed, namely engines, types of gears and pumps for supplying the dispersed and dispersive phases of the product;

– the calculation sequence was established and the design, hydraulic and technological parameters were calculated in relation to quality indicators (average diameter of the fat globules after homogenization), capacity and specific energy costs of the process.

Research results and discussion

The original technological data for the calculation of the jet-slot homogenizer of milk with a separate supply of fat phase using fat normalization are:

– required average diameter of fat globules of milk d_{cp} after homogenization (Kugenev & Barabanshchikov, 1988; Mukhin *et al.* 1976);

– the total productivity of the jet-gap homogenizer Q_r, the minimum values of which for the industrial sample are 1000 kg / h (Mukhin *et al.* 1976), or $2.8 \cdot 10^{-4}$ m^3/s;

– fat content of skim milk, which is at the level of 0.05% for normalization processes (Kugenev & Barabanshchikov, 1988; Krus *et al.* 2002);

– the fat content of cream, which is determined by the technological requirements of the process and according to the results of analytical and experimental studies to obtain a high degree of dispersion should be equal to 40-50% (Samoichuk, 2019b).

The maximum degree of dispersion (0.8 microns) among known machines used in the dairy industry is provided by valve homogenizers (Kalinina & Ganina, 2008). In this case, the average size of fat globules is reduced by 4 times. This is a sufficient indicator in terms of technological processes for the production of dairy products that use homogenization, which makes it possible to accept it as a design parameter of the industrial installation.

In technological lines of dairy production, in most cases, the dispersant is set up after pasteurization (Zakharova *et al.* 2008). When normalization and homogenization are carried out simultaneously, separation operation is preceded by them, which is advisable to conduct at 65-70 °C. The rational values of milk temperature are 60…65 °C (Samoichuk, 2018; Gordesiani, 1990).

Most of the technological instructions governing the production of dairy products to obtain a given dispersion of the finished product are given by the value of the pressure of the valve dispersion (Kugenev & Barabanshchikov, 1988; Loncin & Merson, 1979; Bredikhin & Kosmodemyansky, 2001). It is possible to calculate the average diameter of fat globules after homogenization according to the formula (Kugenev & Barabanshchikov, 1988; Didur *et al.* 2008).

$$d_{ср} = \frac{3,8 \cdot 10^{-3}}{\sqrt{\Delta p_{зн}}}, \qquad (1)$$

where $\boldsymbol{\Delta p_{зн}}$ – the pressure of skim milk supply, MPa.

To determine the performance on skim milk and cream, from the formula (2), the supply of the corresponding components of the emulsion is to be determined (Triguba, 2014)

$$\frac{Q_г}{Ж_в - Ж_{зн}} = \frac{Q_в}{Ж_{н.м} - Ж_{зн}} = \frac{Q_{зн}}{Ж_в - Ж_{н.м}}, \qquad (2)$$

$$Q_г = \frac{Q_{зн}(Ж_в - Ж_{зн})}{\rho_м (Ж_в - Ж_{н.м})}, \qquad (3)$$

$$Q_г = \frac{Q_в \left(Ж_в - Ж_{зн}\right)}{Ж_{н.м} - Ж_{зн}}, \qquad (4)$$

where, $Q_г$, $Q_{зн}$, $Q_в$ – supply of milk normalized by fat content, supply of skim milk and cream, m^3/s; $Ж_{н.м}$, $Ж_{зн}$, $Ж_в$ – fat, respectively, of normal, skimmed milk and cream,%.

If the fat content of the fat phase is not specified by requirements, we recommend using the highest fat content of the product, due to technology, in order to obtain fat globules with a smaller average diameter of each particle. For the calculation we accept $Ж_в$ = 40%, $Ж_{зн}$ = 0,05%, $Ж_{н.м}$ = 3,2%.

The required rate of skim milk for obtaining the product with a given average size of fat particles, is found from the formula (5) (Samoichuk, 2019a)

$$\upsilon_{зн} = \sqrt{\frac{We_к \cdot \sigma_{ж-п}}{2\rho_{пл} \cdot d_{ср} \cdot k_{щ}^2}}, \qquad (5)$$

where $\rho_{пл}$ – density of milk plasma, kg/m^3; $We_к$ – the critical value of Weber criterion; $k_{щ}$ – coefficient of the jet-slot homogenizer; $\sigma_{ж-п}$ – surface tension at the interface between fat and plasma, N/m.

For the calculation we take $We_к$ = 28, $k_{щ}$ = 0,8.

Parameters of the homogenization chamber at the place of the largest narrowing of the jet homogenizer when using a chamber having a cylindrical shape is determined from the formula (6)

$$\upsilon_{зн} = \frac{Q_{зн}}{\varepsilon_к \cdot S}, \qquad (6)$$

where $\varepsilon_к$ – compression ratio for the central part of the chamber, which depends on the chamber shape and is 1 for the inner surfaces having a cylindrical shape; S – intersection area of the chamber of the jet-gap dispersant at the place of greatest narrowing, m^2.

$$S = \frac{\pi \cdot d_{кам}^2}{4}, \qquad (7)$$

where $d_{кам}$ – inner diameter of the slot homogenizer chamber at the place of greatest narrowing, m. (Samoichuk, 2019a)

$$d_{кам} = \sqrt{\frac{4 \cdot Q_{зн}}{\varepsilon_к \cdot \pi \cdot \upsilon_{зн}}}, \qquad (8)$$

For calculating the width of the annular slot for the supply of cream will take the value h = 0.6–0.8 mm, that is the values that were determined during the optimization of experimental data (Samoichuk *et al.* 2019).

The velocity of supply of the fat phase at the point of entry to the movement of the flow of skim milk can be found from the correlation

$$\upsilon_в = \frac{Q_в}{\pi \cdot d_к \cdot h}, \qquad (9)$$

To guarantee the supply of skim milk and the fat phase, volumetric action pumps should be selected, whose excess pressures for selection are calculated from ratios (10) and (11) (Samoichuk, 2019a)

$$\Delta p_{зн} = \frac{8 \cdot Q_{зн}{}^2 \cdot \rho_{зн}}{\mu_к{}^2 \cdot \pi^2 \cdot d_к{}^4}, \qquad (10)$$

$$\Delta p_в = \frac{Q_в{}^2 \cdot \rho_в}{2\mu_в{}^2 \cdot \pi^2 \cdot d_к^2 \cdot h^2}, \qquad (11)$$

where $\mu_к$ – the expense ratio for the inner surfaces of the cylindrical chamber at the place of greatest narrowing is 0.82; $\mu_в$ – the coefficient of costs for the inner surfaces of the confuse and diffuser at the initial site at the point of absorption of the cream into the gap channel, this coefficient was determined experimentally according to the method described in (Samoichuk, 2018), the obtained data are shown in the graph (Fig. 2).

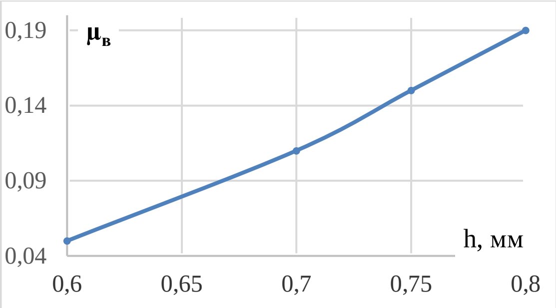

Figure 2. The dependence of the flow factor of the jet-slot homogenizer on the width of the gap

Pump capacities used to drive skim milk and cream supply pumps can be determined from the dependencies

$$P_{в} = \frac{Q_{в} \cdot \Delta p_{в}}{\eta_{в}}, \quad (12)$$

$$P_{зн} = \frac{Q_{зн} \cdot \Delta p_{зн}}{\eta_{нзн}\eta_{пзн}}, \quad (13)$$

where, $\eta_{нв}$ $\eta_{нзн}$ – respectively, the efficiency factors of the pump for supplying fat and skim milk; $\eta_{пзн}$ – the coefficients of the efficiency of the gearbox and gears between the dispersion phase pump and the corresponding motor.

It is suggested for supplying cream in the industrial sample to use BE-G20 HP 0.6 pump, which has an efficiency factor of 0.8. The pump drive uses an АИРЕ 71 L-2 asynchronous electric motor with a power output of 0.55 kW with an efficiency of 0.71. For the delivery of skim milk, the pump НШП-10 is used, which has a maximum productivity of 10 m^3/h at a pressure of 2.4 MPa and an efficiency factor of 0.81. Between it and the engine there is a mounted cylindrical gearbox 1ЦУ-160 with a gear ratio of 2… 2.5 and efficiency of 0.98 (Stepanova, 2000; Walstra *et al.* 1999). The electric pump 3000 s^{-1} АИРС 112 М2 with a capacity of 7.5 kW and an efficiency of 0.84 is used to drive the supply pump of skim milk (Ward, 2015).

The total power of the jet homogenizer is determined from the formula

$$P = \frac{P_{зн} + P_{в}}{\eta_{двв}\eta_{двз}}, \quad (14)$$

where $\eta_{двв}, \eta_{двз}$ – the efficiency of the drive motors of the pumps for supplying skim milk and cream.

The specific energy consumption of the jet-slot milk homogenizer can be defined as

$$E_{пит} = \frac{P}{Q_{г}}, \quad (15)$$

The main design, technological and energy indicators for a typical series of homogenizers in terms of performance are summarized in Table 1.

The obtained results (Table 1) indicate that fat globules, the average diameter of which is within the technologically determined values at the performance of the industrial sample at level 1 and 2.5 t/h can be obtained at the same values of the power of the pump used for the supply of cream, provided that the width of the annular gap is increased by 0.1 mm.

Table 1. Estimated data of sizes of jet-slot homogenizer of milk with separate cream supply

Productivity $Q_г$, t/h	Chamber diameter $d_{кам}$, mm	Gap width h, mm	Power of cream pump, $P_в$, kW	Power of skim milk pump, $P_{зн}$, kW	Total power, P, kW	Specific energy consumption, $E_{пит}$ kW·h/t
1.0	2.60	0.60	0.128	0.616	0.744	0.74
2.5	4.00	0.70	0.128	1.719	1.847	0.74
5.0	5.65	0.75	0.241	3.455	3.696	0.74
10.0	8.00	0.80	0.528	6.876	7.404	0.74

The analysis of the obtained results makes it possible to establish that in order to ensure the productivity of the industrial sample of a jet-slot homogenizer of milk at the level of 10 t/h, the diameter of the chamber at the place of the largest narrowing should be twice smaller than the diameter of the camera in the place of most narrowing at a productivity of 2.5 t/h. The same capacities for the drive of the pumps for supplying cream for productivity of 1 and 2.5 t/h are achieved by increasing the size of the annular gap by 0.1 mm. Subsequently, provided that the width of the gap is increased by 0.05 mm, the required drive power of the cream supply pumps is doubled at 5 and 10 t/h.

Increasing the width of the annular gap is necessary to provide the desired productivity of the industrial sample, the velocity of supplying cream increases from 4.3 m/s for productivity of 1 t/h to 10.5 m/s at a productivity of 10 t/h, which provides technologically required for obtaining required average diameter of the fat globules, difference in velocities of dispersive (44–53 m/s) and dispersed (4.3–10.5 m/s) phases.

Almost 10-fold increase in the required power output for the pump supplying skim milk directly correlates with productivity gains from 1 to 10 t/h as power increases from 0.616 kW to 6.876 kW. The less remarkable increase in the power of pump for cream supplying from 0.128 kW at 1 and 2.5 t/h to 0.528 kW at a productivity of 10 t/h is explained by the gradual increase in the width of the annular slot.

The obtained data indicate a 10-fold reduction in the specific energy consumption of the dispersion process, compared to the most common industrial valve dispersants and a 20% reduction in energy consumption compared to their indicator for the counter-jet homogenizer achieved due to decrease in operation pressure of the process and correspondingly decreasing supply rate of skim milk and cream when arranging the delivery of the fat phase in the place of the largest narrowing, and therefore the maximum difference in the velocity of the phases. Achieving this result is possible when using the design, which principle of action is based on creating the maximum difference between the velocities of the dispersive and dispersed phases.

Conclusions

In order to reduce the energy costs involved in the process of homogenization at implementing jet-slot homogenizer of milk, the method of calculation of the industrial design was developed, which allowed to calculate the basic parameters of a jet-slot homogenizer for productivity of 1-10 t/h. The method of calculation is given for productivity on skim milk and cream, velocity of supply and pressure of skim milk, velocity and pressure of supplying cream, chamber diameter at the place of maximum narrowing, capacity for drive of pumps of supply of skim milk and cream and specific energy costs of the process for industrial homogenizers of the specified performance range.

It was found that the power required to drive a skim milk pump exceeds the pump capacity used to supply cream 4.8 times at a productivity of 1 t/h and 14.3 times at a productivity of 5 t/h. The increase in capacity for the pump supplying skim milk has a direct correlation with the increase in the performance of the jet-slot homogenizer. A less remarkable increase in the capacity of the pump for the supply of cream (4.12 times) with increasing productivity is provided by increasing the width of the annular gap within the values of the parameter determined during optimization.

In the course of further research, the development of an industrial design, the transfer of documentation to the manufacturer, and a further evaluation of the cost-effectiveness of the introduction of the jet-slot homogenizer of milk are planned.

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