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ESTABLISHING AN INTERCONNECTION BETWEEN THE TECHNICAL AND TECHNOLOGICAL PARAMETERS OF MILKING EQUIPMENT BASED ON THE MOVEMENT OF A MILK-AIR MIXTURE IN A MILKING MACHINE

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Machine milking is one of the main technological processes in the dairy industry whose efficiency level largely affects cattle breeding in general. The key role, in this case, belongs to milking equipment. The design and use of technical means of milking are associated with certain difficulties related to the imperfection of milk discharge. Therefore, the current study is due to the need to investigate the process of moving the milk mixture in a milking machine.

A physical-mathematical model of the process of moving the two-phase milk-air mixture along the milk-conducting line of a milking machine has been built. The mathematical model relates the value of the fluctuating of vacuummetric pressure ΔP, the rate of milk discharge Q_M, the pulse rate ζ, and the value of working vacuummetric pressure P. It was found that in the milk-conducting system with the upper milk pipeline there is a large fluctuation of vacuummetric pressure ΔP=1.02–4.69 kPa, which exceeds the regulated value (2.5 kPa). In a milk-conducting system with a lower milk pipeline, the vacuummetric pressure fluctuation is ΔP=0.59–1.84 kPa.

The patterns of change in the value of working pressure P and the frequency of pulsations ζ in the milking machines of simultaneous and pair action depending on the rate of milk discharge from the udder have been determined.

It is established that the maximum deviation of the value of fluctuation of vacuummetric pressure ΔP between the experimental and theoretical data within a predefined range of factors is 0.81 kPa. The correlation coefficient is 0.92, which indicates the adequacy of the constructed models. Owing to this, the task of the rational choice of milking equipment is resolved

Keywords: milking machine, vacuum system, milk-air mixture, milk discharge speed, vacuummetric pressure

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1. Introduction

Dairy farming is an industry that provides for further growth in milk production. Thus, in order to achieve a high level with the lowest labor costs, it is necessary to comprehensively mechanize the technological process of milking cows. This is also necessary to improve the quality of milk and cattle service culture, improve working conditions of milking machine operators [1].

Along the way, there are certain difficulties, in particular, violations of the mode of operation of industrially produced milking plants, depending on the change in the amount of atmospheric pressure.

Despite the large number of theoretical and experimental studies addressing the improvement of industrially produced milking installations, the latter still have certain shortcomings that complicate their effective use [2–4].

In this regard, it is a relevant task to investigate conceptual approaches to the issue of active development of dairy cattle breeding as regards technical support. The relevance is due to the trends in the development of milk production and the development of new procedures for defining the system of indicators and recommendations for the selection of resource potential.

Thus, the current study is due to the need to investigate the process of moving the milk mixture in a milking machine.

Such approach would make it possible to address various violations in the management of machine milking and obtaining high-quality milk. This could improve the performance of technological equipment. At the same time, this would reveal the mechanism of interaction between milk and milking equipment, which is both theoretically and practically interesting.

2. Literature review and problem statement

Paper [5] states that various designs of milking machines are used at dairy plants.

Work [6] establishes certain shortcomings inherent in the structures of milking machines when milking high-performance cows. Thus, it is noted that such basic element is rubber products that are used in structures. In work [7], it is established that during the period of intensive milk production in a cow when milk leaves the collector, a milk plug may form in the lower part of the milk hose. It blocks the access of rarefaction from the milk pipeline to the suction cups' chambers, which leads to a sharp decrease in rarefaction. That affects the possible inhibition of the milk yield reflex and fluctuations with the destabilization of the vacuum milking regime. As a result, this could lead to overflow of the milk collection chamber of the collector, the reverse outflow of milk, the descending of the suspended part from the udder of the cow [8]. Thus, there is a problem of removing milk from the milk collection chamber of the collector into the upper milk pipeline. This is especially true of the process of machine milking of highly productive cows when there is an untimely discharge of milk from the collector and the pulsation of the flow in the milk hose.

A promising direction in the construction of milking machines is to design milking machines that cope with large flows of milk from high-performance cows, providing complete and safe milking [9].

The transportation property of the milking machine does not always correspond to the intensity of milking. According to [10], at the maximum intensity of milk yield, when milking with typical milking machines, a reverse flow of milk may occur. This is due to the overflow of the milk collection chamber of the collector and the milk of the conductive hose with milk. The values and level of vacuum pressure are reduced.

The same opinion was reached by scientists in [11]. It is proved that milking machines, which are used in practice both in synchronous and pair milking, do not always cope with high milk yield in cows. That increases the milking time, as well as the risk of disease of the cow's mammary gland. Given the large flows of milk, the milk collection chamber of the collector overflows, there is a reverse outflow of milk, destabilization of vacuum regimes in the suction chambers of milking cups. All this necessitates the design of milking machines that could make it possible to easily milk cows with any productivity.

There are several ways to solve the problems of complete and rapid milking of high-performance cows [12]. These include the use of collectors with an increased volume of the milk collection chamber, an increase in the diameters of milk hoses and tubes, milking under an increased vacuum, collectors with upper milk evacuation. However there remained unresolved issues related to the correspondence of the physiologicality of equipment to biological objects – dairy cows, their impact on the process of milk production.

In [13], the oscillations of vacuummetric pressure in the under-the-teat space is divided into two categories:

– accidental, caused by various violations of the rules of machine milking and failures of systems that are eliminated in the process of operation;

– systematic, related to imperfection and mismatch between the structural and technological parameters of milking equipment and the nature of the milking process.

That division confirms the fact that there are a number of shortcomings of milking equipment whose elimination is impossible without conducting appropriate research. Namely, the establishment of the relationship of technical and technological parameters of milking equipment depending on the movement of the milk mixture in a milking machine.

Much attention was paid to solving the problem of stabilization of the vacuum regime of milking installations. Recommendations for determining the main parameters of vacuum lines, taking into consideration the limiting factor – the maximum permissible fluctuations in vacuummetric pressure during milking, have been developed.

The joint movement of milk and air can be characterized by the presence of various forms of flow [14]. When the mixture moves along a milk pipeline, its air phase can be distributed throughout the cross-section of the hose both in the form of small air bubbles and in the form of large clusters that occupy the entire section of the pipeline. In addition, the air can move in the center of the pipeline while the liquid is distributed at the edges, forming a film, and the boundaries of the phase section can take both smooth and wavy shapes [15]. Therefore, it can be argued that there is no consensus on the modes of movement of the milk-air mixture in a milking machine. This is due to objective difficulties since the process of cow milking is extremely variable.

The lack of proper information makes it impossible to fully assess the manufacturability of milking and dairy equipment depending on geometrical parameters and structural execution.

Thus, as noted in [16], in order to improve the structural elements of milking and dairy equipment, it is necessary to establish the relationship between the technical and technological parameters of the equipment depending on the movement of the milk mixture in a milking machine.

In order to eliminate various violations in the management of machine milking and obtain high milk yields, it is necessary to investigate the interaction between the milk-air mixture and milking equipment [17].

All this suggests that it is advisable to conduct a study on the process of moving the milk mixture in a milking machine.

Thus, addressing the issue related to improving the efficiency of machine milking requires the investigation, refinement, and improvement of key elements in the system of technical means, which is of both scientific and practical interest.

3. The aim and objectives of the study

The purpose of this study is to establish the mathematical relationship between the technical and technological parameters of milking equipment that could ensure the efficiency of the milking process.

To accomplish the aim, the following tasks have been set:

– to carry out numerical modeling of the movement of the milk-air mixture in a milking machine;

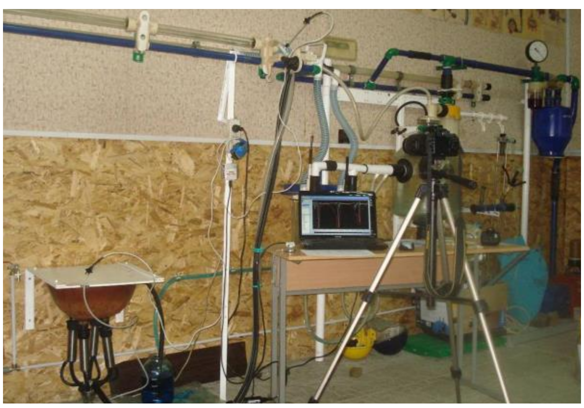
– to experimentally investigate the movement of the milk mixture in a milking machine;

– to establish the adequacy of the mathematical models of movement of the milk-air mixture in a milking machine.

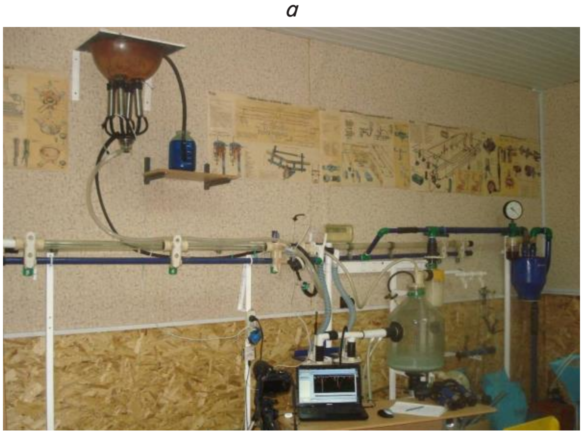
4. The study materials and methods

Control and compliance of the characteristics and parameters of milking equipment are regulated by the international standards ISO 5707 and ISO 6690 [18]. They contain procedures for assessing the state of functioning of the vacuum and milking system of milking plants. At the same time, they do not specify the procedures for researching the process of the movement of the milk-air mixture in a milking machine.

For the relevant research, an experimental bench of milking equipment was designed and fabricated, which fully meets the requirements set by ISO 5707. In addition, the fabricated bench has all the necessary connecters for connecting measuring equipment in accordance with ISO 3918 (Fig. 1). It is possible to simulate the technological process of milking on various milking machines for various milk-conducting systems.



a



b

Fig. 1. Experimental bench of milking equipment: *a* – with an upper milk pipeline; *b* – with a lower milk pipeline

The value of the vacuummetric pressure of the vacuum system of the milking unit was determined using a vacuum regulator. The pulsation rate was set using the appropriate regulators on the pulsators of milking machines. Milk yield was modeled on an artificial udder. The speed of milk discharge was changed with the help of calibrated nozzles. The diagram of connection of the measuring equipment to milking machines of simultaneous and pair action is shown in Fig. 2.

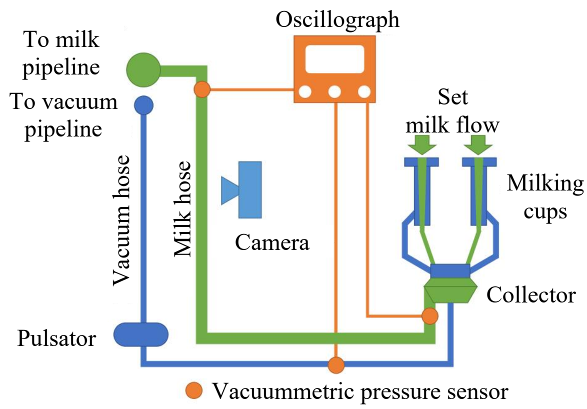


Fig. 2. Schematic connection of measuring equipment to milking machines

As objects of research, we selected: the two-stroke milking machine of simultaneous action «Mayga» (Ukraine) and the milking machine of pair action Milk-Rite (USA).

Factors in the study of the process are the working pressure of the vacuum system P (45–55 kPa), the pulse rate ζ (40–80 min^{-1}), the rate of milk discharge Q_M (0.4–2.0 l/min).

The fixed values of some parameters of milking equipment: the length of the milk hose is 2.5 m; the diameter of the milk hose is 14 mm. The distance between the upper milk pipeline and the suspended part of the milking machine was 1.4 m, and the distance between the lower milk pipeline and the suspended part of the milking machine was 1.0 m.

Evaluation criteria: the value of vacuum fluctuation ΔP and the performance of the milking machine q.

A change in the vacuummetric pressure in the system was determined using the pressure sensor MPX5100DP (The Netherlands) and was processed by the NI USB-6008 analog-digital converter (USA) and a personal computer equipped with the NI SignalExpress 2012 software package (USA).

Vacuum fluctuation is calculated as the standard deviation of vacuum pressure:

$$\Delta P = \sqrt{\frac{1}{j}\sum_{i=1}^{j}\left(P_i - P_{ave}\right)^2}, \quad (1)$$

where P_i is the value of vacuummetric pressure, Pa; P_{ave} – the average value of vacuummetric pressure, Pa; j is the number of measurements.

The productivity of the milking machine is the ratio of the volume of fluid that passed through it per unit of time:

$$q = \frac{V_c}{t_c}, \quad (2)$$

where V_c is the volume of fluid that passed through the milking machine, m^3, t_c – the time during which the volume of liquid V_c passed, s.

The volume of fluid that passed through the milking machine was determined using a measuring tank, and time – with the help of the stopwatch SOPpr-2a-3-000.

The mode of flow of the milk-air mixture was determined visually using the Nikon D3100 (Japan) camera in a video mode. The calibration of the modes of the flow of the milk-air mixture is as follows: intermittent, distributive, separate and transitional currents.

The research is carried out according to the Box-Benkin second-order plan for 3 factors [19]. The levels of variations in factors were selected based on the results of numerical modeling of the movement of the milk mixture in the milking machine. The experiments are carried out three times.

5. Results of studying the movement of the milk-air mixture in the milking machine

5. 1. Numerical modeling of the movement of the milk-air mixture in the milking machine

Milk-conducting systems in modern milking plants can be divided into two types: with the upper and lower milk pipelines. The modes of flow of the milk-air mixture in each of these systems differ, so it becomes necessary to investigate them.

Numerical modeling was carried out in the Star CCM+ software package (Germany). The grid of a 3D model of the milk hose of a milking machine for two types of milk-conducting systems using the model of surface mesh generator and multifaceted cells was constructed. Cell size: 0.001 m.

The simulations were carried out using the Euler's multiphase model and by the volumetric fluid method. The movement of the milk-air mixture is subject to the k–ε turbulence model. The thermodynamic state of the milk-air mixture was assumed to be isothermal. The liquid of the milk-air mixture has a constant density, and its gas (air) is ideal.

At the initial time point, the milk hose was filled only with gas (air), that is, the gas content was $\alpha=1$. The roughness of the surface of the milk hose was $\varepsilon=2.4\cdot10^{-6}$ m.

At the inlet of the milk hose of the milking machine, the airflow through the conductive channel collector (diameter, $d_{col}=10^{-4}$ m) is $Q_{G(A\text{-}A)}=3.3\cdot10^{-5}$ m^3/s (2 l/min), while the air speed is $U_{G(A\text{-}A)}=0.00427$ m/s.

Milk at the inlet of the milk hose of the milking machine comes in portions with a certain frequency. For a two-stroke milking machine of simultaneous action, the pulse chart of vacuummetric pressure in the inter-wall space of milking cups takes the form shown in Fig. 3 and is characterized by two parameters – the pulse rate ζ and the A+B phase.

When milking, during the discharge period (phase $A+B$), a portion of milk is excreted from teats and enters the milk hose through the collector. According to [20], the flow of milk $Q_{L(A\text{-}A)\max}$ during discharge (the rate of milk discharge from cow's teats) can vary from 0.4 l /min (6,67·10^{-6} m^3/s) up to 2 l/min (3,33·10^{-5} m^3/s). With an internal diameter of the milk hose $D=0.014$ m, the milk speed $U_{G(A\text{-}A)}$ varies from 0.0433 m/s to 0.216 m/s.

According to [20], the pulse rate ζ can range from 40 min^{-1} to 80 min^{-1}, and the $A+B$ phase – in the range from 0.4 to 0.8. At the outlet of the milk hose, there is a constant vacuummetric pressure $P_{B\text{-}B}$, which can be measured within the permissible limits from 45 kPa to 55 kPa [20]. Therefore, our numerical modeling was carried out according to a complete plan of experiments for four factors at three levels.

As a result of numerical modeling of the process of moving the milk mixture in a milking machine of simultaneous action in the upper milk pipeline, the distribution of the fluid content of 1–α along the length of the milk hose was obtained (Fig. 4). The cross-sections of the milk hose at characteristic points are shown in Fig. 6 in the form of separate circles.

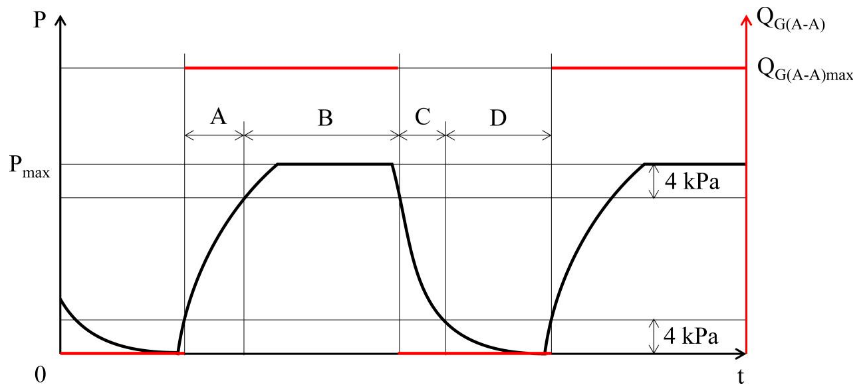


Fig. 3. Pulse charts of vacuummetric pressure P in the inter-wall space of milking cups and milk flow over a discharge period $Q_{G(A\text{-}A)}$

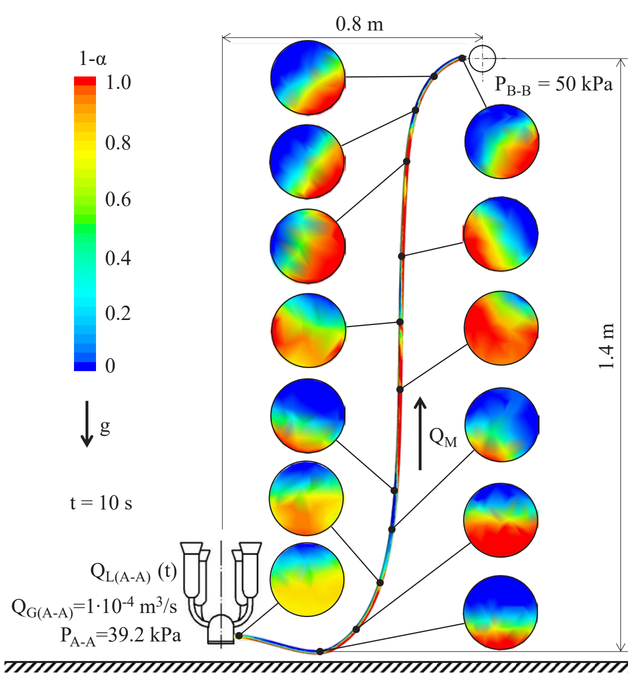


Fig. 4. Distribution of fluid content 1–α along the length of the milk hose of the milking machine at the upper milk pipeline at a pulse rate of ζ=60 min^{-1} and its phase $A+B$=0.6

Fig. 5 shows that the flow of the milk-air mixture on the vertical section of the milk hose is intermittent according to the map of the flow of the two-phase medium.

Due to the occurrence of intermittent flow of the milk mixture at the inlet of the milk hose, vacuummetric pressure fluctuation is observed (Fig. 6), which adversely affects the technological process of machine milking.

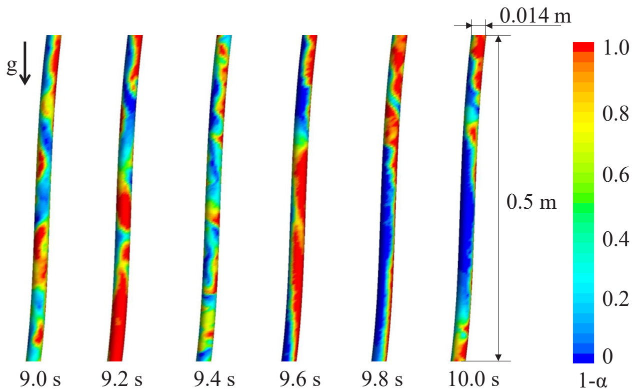


Fig. 5. Flow of milk-air mixture on the vertical section of the milk hose of the milking machine of simultaneous action (with the upper milk pipeline)

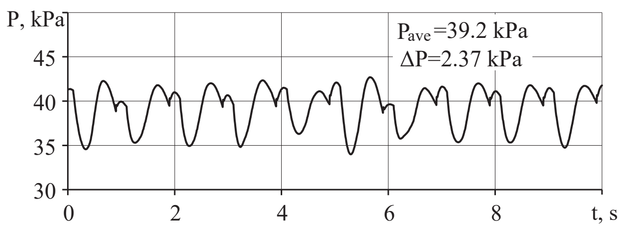


Fig. 6. Vacuummetric pressure fluctuation at the inlet of the milk hose of the milking machine of simultaneous action at $\zeta=80$ min^{-1}, $A+B=0.6$, $Q_{L(A\text{-}A)max}=6.67\cdot10^{-6}$ m^3/s, $P=50$ kPa (with an upper milk pipeline)

Using the Mathematica (France) software package, by the least-square method, we approximated the obtained data according to the selected experiment plan; a mathematical model of the relationship between the fluctuation (standard deviation) of vacuummetric pressure and the factors of numerical modeling was built:

$$\Delta P=-1.3813+0.490741(A+B)-$$
$$-0.509259(A+B)^2-0.0567639\zeta+$$
$$+0.00069444(A+B)\zeta+$$
$$+0.00051852\zeta^2+$$
$$+0.0604815P+$$
$$+0.00277778(A+B)P+$$
$$+0.00044444\zeta P-$$
$$-0.00014814P^2+$$
$$+1.05162Q_M+$$
$$+0.104167(A+B)Q_M-$$
$$-0.00017361\zeta Q_M+0.020254Q_M^2. \quad (3)$$

The graphical interpretation of the resulting mathematical model (3) is shown in Fig. 7.

Fig. 7, *a, b*, and dependence (3) demonstrate that with an increase in the values of the rate of milk discharge Q_M, the pulsation rate ζ, and the value of the working vacuummetric pressure P, there is an increase in the standard deviation of the vacuummetric pressure ΔP. Regarding the size of the phase of pulsations $A+B$, it can be argued that it has little effect on the fluctuation of vacuummetric pressure ΔP.

Therefore, in further experimental studies, the pulsation phase $A+B$ will be fixed at the regulated value $A+B=0.6$.

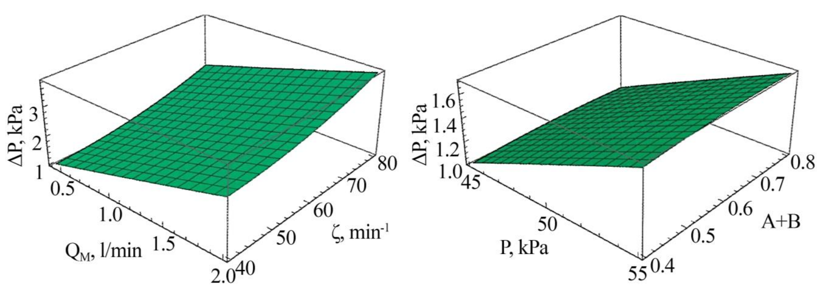
As a result of our numerical modeling of the process of moving the milk mixture in the milking machine of simultaneous action in a lower milk pipeline, the distribution of the liquid content $1-\alpha$ along the length of the milk hose was established (Fig. 8).

In contrast to the connection to the upper milk pipeline, at the lower connection there is a separate flow of the milk-air mixture according to the map of the flow of the two-phase medium. In this case, there is a slight fluctuation in the vacuummetric pressure $\Delta P=0.59$–2.27 kPa (Fig. 9), which does not depend on the $A+B$ phase value and vacuummetric pressure P:

$$\Delta P=2.76713-0.072831\zeta+0.00060787\zeta^2+$$
$$+0.0450231Q_M+0.350405Q_M^2. \quad (4)$$

The graphical interpretation of the resulting mathematical model (4) is shown in Fig. 10.

Thus, it was established that, unlike the connection to the upper milk pipeline, at the lower connection there is a separate flow of the milk-air mixture.



a *b*

Fig. 7. Dependence of change in the standard deviation of the vacuummetric pressure ΔP of the milking machine of simultaneous action (with an upper milk pipeline) on: *a* — the rate of milk discharge Q_M and the frequency of pulsations ζ; *b* — the values of the working vacuummetric pressure P and the phase of pulsations $A+B$

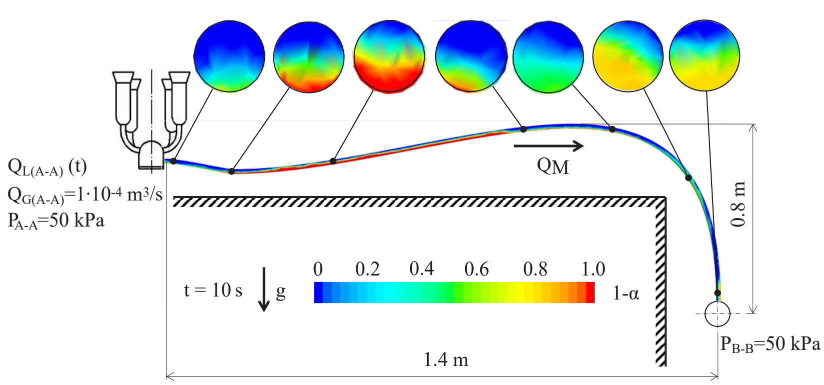


Fig. 8. Distribution of fluid content $1-\alpha$ along the length of the milk hose of the milking machine of simultaneous action at a pulsation rate of $\zeta=60$ min^{-1} and phase $A+B=0.6$ (with a lower milk pipeline)

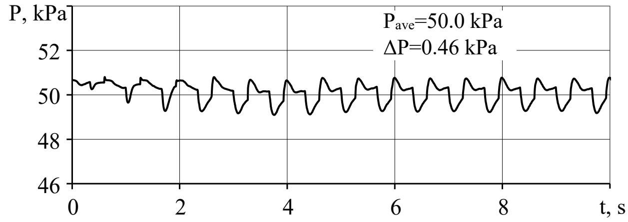


Fig. 9. Vacuummetric pressure fluctuation at the inlet of the milk hose of the milking machine of simultaneous action at a pulse rate of ζ=60 min^{-1} and phase $A+B$=0.6 (with a lower milk pipeline)

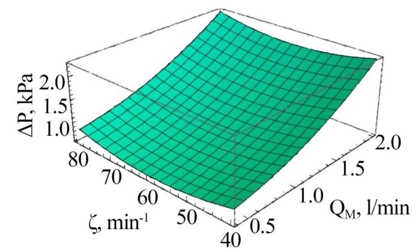


Fig. 10. The dependence of change in the standard deviation of the vacuummetric pressure ΔP of the milking machine of simultaneous action (with a lower milk pipeline) on the rate of milk discharge Q_M and the frequency of pulsations ζ

5. 2. Results of the experimental studies of the process of the movement of the milk-air mixture in the milking machine

In accordance with the devised methodology for experimental studies of the process of the movement of the milk mixture in the milking machine, we obtained, for each experiment, the dynamics of vacuummetric pressure at three points of the milking machine: a pulsator, a collector, a milk tap.

A mathematical model was built of the influence of the investigated factors on the fluctuation of vacuummetric pressure for the upper milk pipeline with a milking machine of simultaneous action, which can be represented as:

$$\Delta P_{UMPSA} = 4.41875 - 0.031625\zeta + 0.0006\zeta^2 - 3.09375Q_M - 0.0101563Q_M\zeta + 0.089375Q_M P - 0.06P, \quad (5)$$

where ΔP is the vacuummetric pressure fluctuation, kPa, Q_M – milk discharge rate, l/min, ζ – pulse rate, min^{-1}, P is the working pressure of vacuum system, kPa.

Cochrane's criterion value is G=0.1463<$G_{0.05}$(2, 15)=0.3346. Fisher's criterion value is F=2.09<$F_{0.05}$(8, 30)=2.27. The model is adequate.

Analyzing (5) allows us to argue that the fluctuation of vacuummetric pressure for an upper milk pipeline in the milking machines of simultaneous action is influenced by all the above factors (Fig. 11).

At the same time, with an increase in the rate of milk discharge, the pulse rate of the milking machine and working pressure of the vacuum system, the fluctuation of vacuummetric pressure also increases.

In addition, for the variant with an upper milk pipeline in the milking machine of simultaneous action, a mathematical model was built of the influence of the investigated factors on the performance of the milking machine, which can be represented in the following form:

$$q_{UMPSA} = -13.6555 + 0.143555Q_M^2 + 0.0388125\zeta - 0.000323438\zeta^2 - 1.30156Q_M + 0.0384375Q_M P + 0.53125P - 0.005525P^2, \quad (6)$$

where q is the performance of the milking machine, l/min.

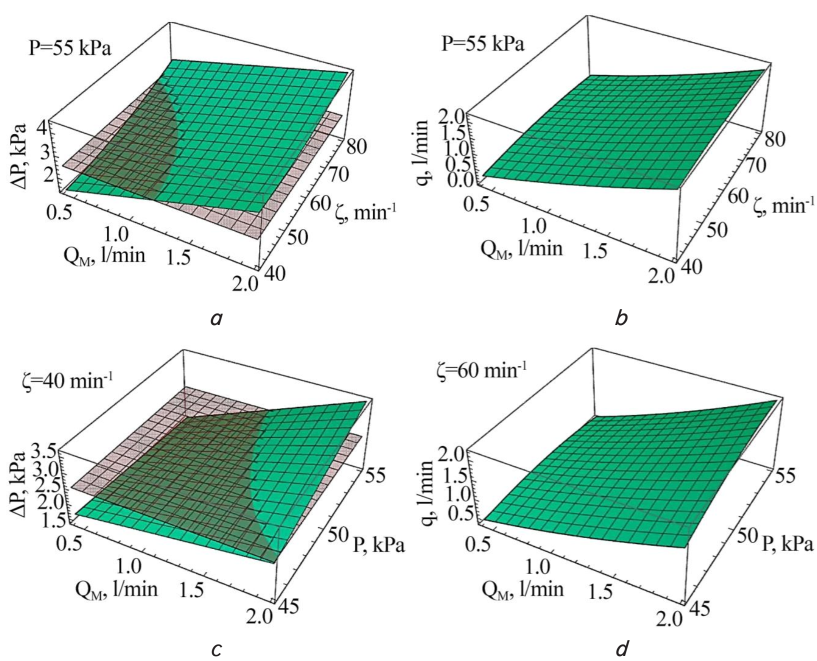


Fig. 11. Dependence of changes in criteria on the factors of studying the upper milk pipeline with a milking machine of simultaneous action: *a* – change in the fluctuation of vacuummetric pressure ΔP depending on the rate of milk discharge Q_M and the frequency of pulsations ζ; *b* – change in the performance of the milking machine q depending on the rate of discharge of milk Q_M and the frequency of pulsations ζ; *c* – change in the fluctuation of vacuummetric pressure ΔP depending on the rate of milk discharge Q_M and working pressure of the vacuum system P; *d* – change in the performance of the milking machine q depending on the speed of milk discharge Q_M and working pressure of the vacuum system P

Cochrane's criterion value is $G=0.1575<G_{0.05}(2, 15)=0.3346$. Fisher's criterion value is $F=2.07<F_{0.05}(8, 30)=2.27$. The model is adequate.

Analyzing (6) allows us to argue that the performance of the milking machine of simultaneous action with an upper milk pipeline is influenced by all the above factors (Fig. 11). At the same time, with an increase in the rate of milk discharge and vacuummetric pressure, the productivity of the milking machine also increases, and when the values of the pulsation rate of the milking machine are varied, the productivity of the milking machine reaches an optimum:

$$q_{UMPSA}\left(Q_M=2.0\,\text{l/min};\ \zeta=60\,\text{min}^{-1};\ P=55\,\text{kPa}\right)= \\ =2.21\,\text{l/min}. \quad (7)$$

According to the analysis of zootechnical requirements, the fluctuation of vacuummetric pressure should not exceed 2.5 kPa. At the same time, the productivity of the milking machine should be maximum, therefore, in order to obtain optimal values of factors, it is necessary to solve a system of equations and inequalities:

$$\begin{cases} \Delta P(Q_M,\zeta,P)<2.5, \\ q(Q_M,\zeta,P)\rightarrow \max, \\ 0.4<Q_M<2.0. \end{cases} \quad (8)$$

Solutions to the system of equations and irregularities (5), (6), (8) for the option with an upper milk pipeline in the milking machines of simultaneous action are the dependences of the pulse rate and working pressure of the vacuum system on the speed of milk discharge. Their graphical interpretation is shown in Fig. 12.

A mathematical model was built of the influence of the investigated factors on the fluctuation in vacuummetric pressure for an upper milk pipeline in the milking machine of pair action, which can be represented in encoded form:

$$\Delta P_{UMPPA}=-21.1898+1.65781Q_M- \\ -0.278646Q_M^2+0.055\zeta- \\ -0.000458333\zeta^2+0.728833P-0.00683333P^2. \quad (9)$$

Cochrane's criterion value is $G=0.2147<G_{0.05}(2, 15)=0.3346$. Fisher's criterion is $F=2.08<F_{0.05}(9, 30)=2.21$.

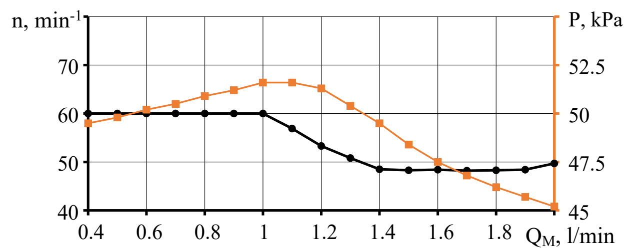


Fig. 12. Dependence of the pulsation rate ζ and working pressure P of the vacuum system on the rate of milk discharge Q_M for the option with an upper milk pipeline in the milking machine of simultaneous action

Analyzing (9) allows us to argue that the fluctuation of vacuummetric pressure for an upper milk pipeline in the milking machine of pair action is influenced by all the above factors (Fig. 13).

At the same time, with an increase in the rate of milk discharge, the fluctuation of vacuummetric pressure also increases, and the pulsation rate of the milking machine and working pressure of the vacuum system do not significantly affect the specified criterion.

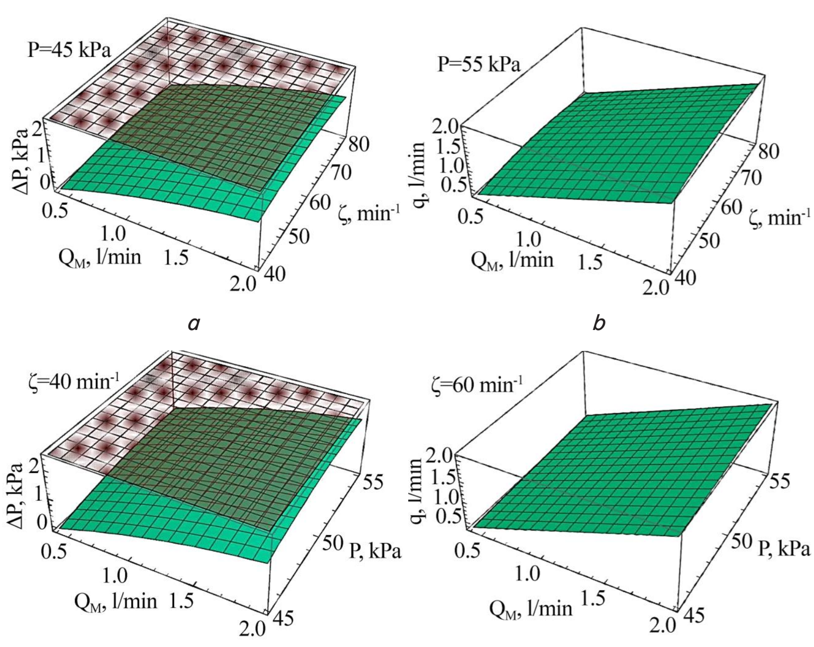


Fig. 13. Dependence of changes in criteria on the factors of studying the upper milk pipeline in a milking machine of pair action: *a* — change in the fluctuation of vacuummetric pressure ΔP depending on the rate of milk discharge Q_M and the frequency of pulsations ζ; *b* — change in the performance of the milking machine q depending on the rate of discharge of milk Q_M and the frequency of pulsations ζ; *c* — change in the fluctuation of vacuummetric pressure ΔP depending on the rate of milk discharge Q_M and working pressure of the vacuum system P; *d* — change in the performance of the milking machine q depending on the speed of milk discharge Q_M and working pressure of the vacuum system P

In addition, for the variant with an upper milk pipeline in the milking machine of pair action, a mathematical model was built of the influence of the investigated factors on the performance of the milking machine, which can be represented in a coded form:

$$q_{UMPPA} = -2.14085 + 1.00734 Q_M + 0.0465125\zeta - 0.000387604\zeta^2 + 0.015P. \quad (10)$$

Cochrane's criterion value is $G=0.2686<G_{0.05}(2, 15)=0.3346$. Fisher's criterion value is $F=1.88<F_{0.05}(11, 30)=2.13$.

Analyzing equation (10) allows us to argue that the performance of the milking machine of pair action with an upper milk pipeline is influenced by all the above factors (Fig. 13). At the same time, with an increase in the rate of milk discharge and vacuummetric pressure, the productivity of the milking machine also increases, and when the values of the pulsation rate of the milking machine are varied, the productivity of the milking machine reaches an optimum:

$$q_{UMPPA}\left(Q_M = 2.0\ \text{l/min};\ \zeta = 60\ \text{min}^{-1};\ P = 55\ \text{kPa}\right) = 2.09\ \text{l/min}. \quad (11)$$

Solutions to the system of equations and irregularities (8) to (10), for the variant with an upper milk pipeline in a milking machine of pair action are the pulse rate $\zeta=60$ min^{-1} and working pressure of the vacuum system $P=54.9$ kPa.

A mathematical model was built of the influence of the investigated factors on the fluctuation of vacuummetric pressure for the lower milk pipeline in a milking machine of simultaneous action, which can be represented in encoded form:

$$\Delta P_{LMPSA} = 2.92625 + 0.328125 Q_M^2 - 0.971875 Q_M + 0.0178125 Q_M \zeta - 0.078\zeta + 0.0006375\zeta^2. \quad (12)$$

Cochrane's criterion value is $G=0.1161<G_{0.05}(2, 15)=0.3346$. Fisher's criterion value is $F=2.11<F_{0.05}(9, 30)=2.21$.

Analyzing equation (12) allows us to argue that the fluctuation of vacuummetric pressure in a lower milk pipeline with the milking machine of simultaneous action is influenced by the speed of milk discharge and the pulse rate of the milking machine (Fig. 14). At the same time, with an increase in the rate of milk discharge and the pulse rate of the milking machine, the fluctuation of vacuummetric pressure also increases.

In addition, for the variant with a lower milk pipeline in the milking machine of simultaneous action, a mathematical model was built of the influence of the investigated factors on the performance of the milking machine, which can be represented in coded form:

$$q_{LMPSA} = -18.5434 + 0.161784 Q_M^2 + 0.04125\zeta - 0.000388021\zeta^2 - 1.91094 Q_M + 0.0503125 Q_M P + 0.744583P - 0.00775833P^2. \quad (13)$$

Cochrane's criterion value is $G=0.1842<G_{0.05}(2, 15)=0.3346$. Fisher's criterion value is $F=1.88<F_{0.05}(7, 30)=2.33$.

Analyzing equation (13) allows us to argue that the performance of the milking machine of pair action with a lower milk pipeline is influenced by all the above factors (Fig. 14). At the same time, with an increase in the rate of milk discharge and vacuummetric pressure, the productivity of the milking machine also increases, and when the values of the pulsation rate of the milking machine are varied, the productivity of the milking machine reaches an optimum:

$$q_{LMPSA}\left(Q_M = 2.0\ \text{l/min};\ \zeta = 53.3\ \text{min}^{-1};\ P = 55\ \text{kPa}\right) = 2.39\ \text{l/min}. \quad (14)$$

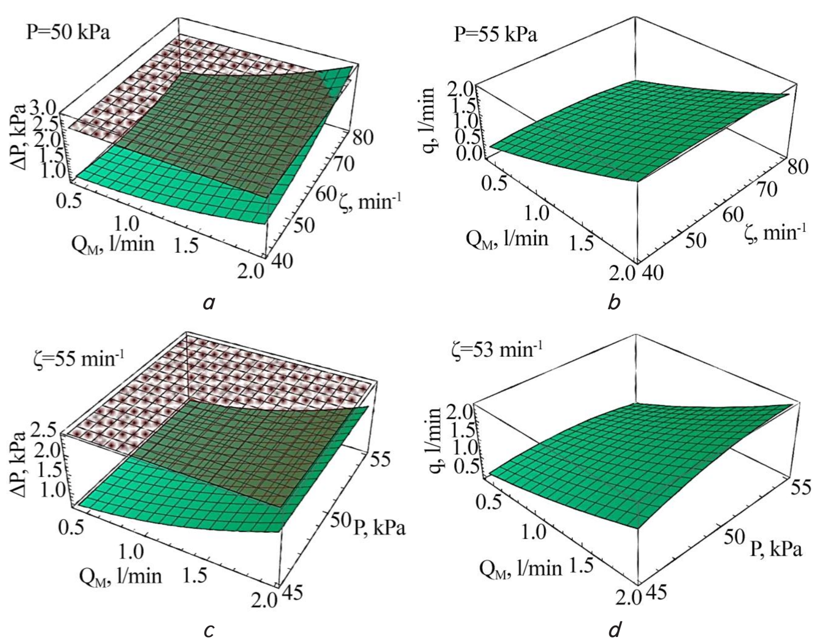


Fig. 14. Dependence of changes in criteria on the factors of studying a lower milk pipeline in the milking machine of simultaneous action: *a* – change in the fluctuation of vacuummetric pressure ΔP depending on the rate of milk discharge Q_M and the frequency of pulsations ζ; *b* – change in the performance of the milking machine q depending on the rate of discharge of milk Q_M and the frequency of pulsations ζ; *c* – change in the fluctuation of vacuummetric pressure ΔP depending on the rate of milk discharge Q_M and working pressure of the vacuum system P; *d* – change in the performance of the milking machine q depending on the speed of milk discharge Q_M and working pressure of the vacuum system P

Solutions to the system of equations and irregularities (12), (13), (8) for the option with a lower milk pipeline in the milking machine of simultaneous action are the dependences of the pulse rate and working pressure of the vacuum system on the speed of milk discharge. Their graphical interpretation is shown in Fig. 15.

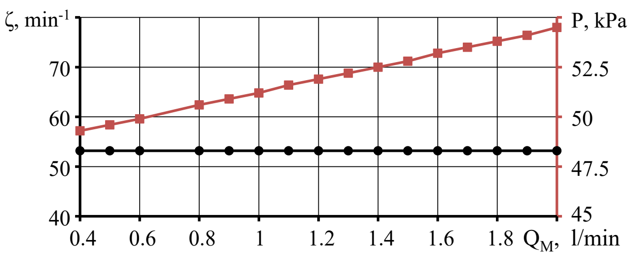


Fig. 15. Dependence of the pulsation rate ζ and working pressure of the vacuum system *P* on the rate of milk discharge Q_M for the variant with a lower milk pipeline in the milking machine of simultaneous action

A mathematical model was built of the influence of the investigated factors on the fluctuation of vacuummetric pressure for a lower milk pipeline in the milking machine of pair action, which can be represented in encoded form:

$$\Delta P_{LMPPA} = 0.6. \quad (15)$$

Cochrane's criterion value is $G=0.1217<G_{0.05}(2, 15)=0.3346$. Fisher's criterion value is $F=1.20<F_{0.05}(14, 30)=2.04$.

Analyzing equation (15) allows us to argue that the fluctuation of vacuummetric pressure in a lower milk pipeline in the milking machines of pair action is not affected by any of the factors (Fig. 16).

In addition, for the variant with a lower milk pipeline in the milking machine of pair action, a mathematical model was built of the influence of the investigated factors on the performance of the milking machine, which can be represented in an encoded form:

$$\begin{aligned} q_{LMPPA} &= -6.05594 - 0.134766Q_M^2 + 0.009\zeta - \\ &- 0.000096875\zeta^2 + 0.378125Q_M + \\ &+ 0.0021875Q_M\zeta + 0.014375Q_MP + \\ &+ 0.229P - 0.00225P^2. \end{aligned} \quad (16)$$

Cochrane's criterion value is $G=0.2394<G_{0.05}(2, 15)=0.3346$. Fisher's criterion value is $F=1.95<F_{0.05}(7, 30)=2.33$.

Analyzing (16) allows us to argue that the performance of the milking machine of pair action with a lower milk pipeline is influenced by all the above factors (Fig. 16).

At the same time, with an increase in the rate of milk discharge and vacuummetric pressure, the productivity of the milking machine also increases, and when the values of the pulsation rate of the milking machine are varied, the productivity of the milking machine reaches an optimum:

$$\begin{aligned} &q_{UMPSA}\left(Q_M = 2.0\,\text{l/min};\ \zeta = 69\ \text{min}^{-1};\ P = 55\ \text{kPa}\right) = \\ &= 1.99\ \text{l/min}. \end{aligned} \quad (17)$$

Solutions to the system of equations and inequalities (15), (16), (8) for the variant with a lower milk pipeline in the milking machine of simultaneous action are the dependences of the pulse rate and working pressure of the vacuum system on the speed of milk discharge. Their graphical interpretation is shown in Fig. 17.

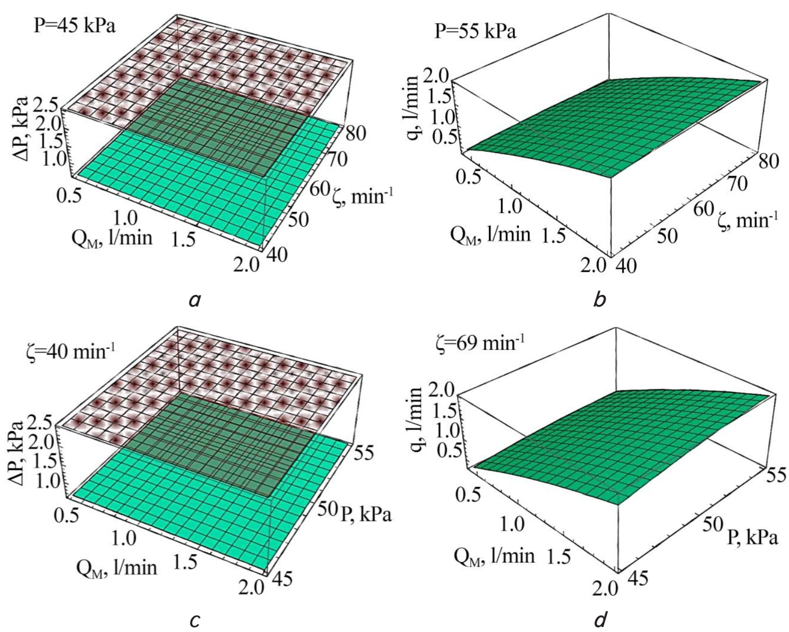


Fig. 16. Dependence of changes in criteria on the factors of studying a lower milk pipeline in the milking machine of simultaneous action: *a* — change in the fluctuation of vacuummetric pressure Δ*P* depending on the rate of milk discharge Q_M and the frequency of pulsations ζ; *b* — change in the performance of the milking machine *q* depending on the rate of discharge of milk Q_M and the frequency of pulsations ζ; *c* — change in the fluctuation of vacuummetric pressure Δ*P* depending on the rate of milk discharge Q_M and working pressure of the vacuum system *P*; *d* — change in the performance of the milking machine *q* depending on the speed of milk discharge Q_M and working pressure of the vacuum system *P*

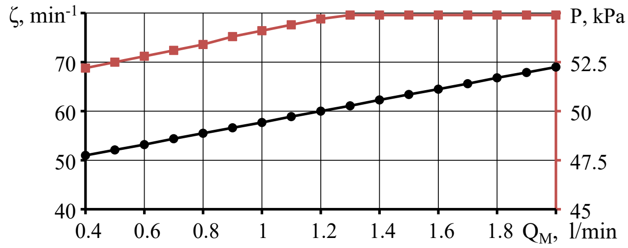


Fig. 17. Dependence of the pulsation rate ζ and working pressure P of the vacuum system on the rate of milk discharge Q_M for the variant with a lower milk bench in the milking machine of pair action

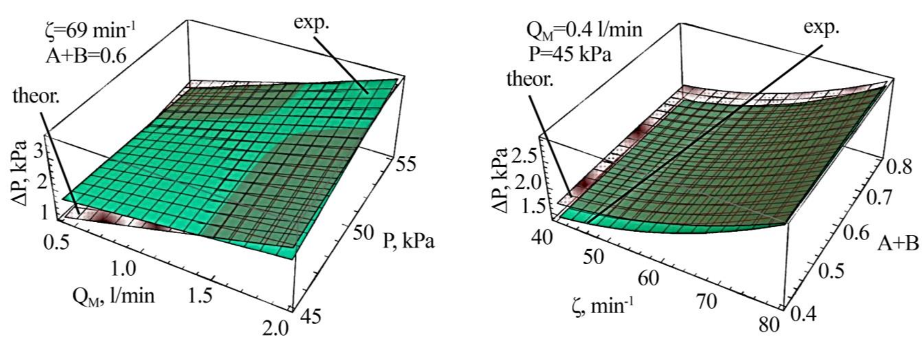
Analysis of the acquired video files of the process of moving the milk mixture along a milk hose of the milking machine has made it possible to draw the following conclusions. For the upper milk pipeline option, the mode of flow of the milk-air mixture is distributive (the liquid covers the edge of the hose, and the gas moves inside) with an instant switch to intermittent flow (a cork of liquid is formed). For the variant with a lower milk pipeline, another mode of flow of the milk-air mixture is observed, namely the separate flow (the liquid and gas move separately, while creating a clear interface). That is, the use of a lower milk pipeline in milking plants makes it possible to obtain milk without air bubbles.

5. 3. Results of establishing the adequacy of the mathematical models of the process of moving the milk mixture in the milking machine

For comparing the mathematical models of the process of moving the milk mixture in the milking machine of simultaneous action with an upper milk pipeline, built on the basis of our numerical modeling and experimental studies, plots of the corresponding dependences (3), (5) (Fig. 18) were constructed. The maximum deviation of the vacuummetric pressure fluctuation between the experimental and theoretical data in a given range of factors is 0.81 kPa, the correlation coefficient is 0.92, and the Fisher's criterion is $2.01 < F_{table}(0.05;5;30) = 2.53$.

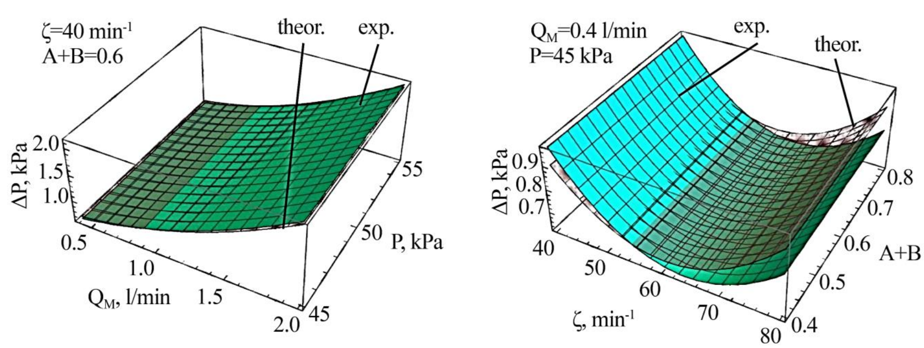
For comparing the mathematical models of the process of moving the milk mixture in the milking machine of simultaneous action in a lower milk pipeline, obtained in numerical modeling, and the experimental studies, plots of the corresponding dependences (4) and (12) (Fig. 19) were constructed. The maximum deviation of the vacuummetric pressure fluctuation between the experimental and theoretical data in a given range of factors is 0.34 kPa, the correlation coefficient is 0.93, and the Fisher's criterion is $2.13 < F_{table}(0.05;5;30) = 2.53$.

Our analysis of Fig. 18, 19 reveals that the nature of the theoretical and experimental dependences is the same; the high correlation coefficient indicates the adequacy of the constructed theoretical models.



a *b*

Fig. 18. Theoretical and experimental dependences of changes in the fluctuation of vacuummetric pressure ΔP in an upper milk pipeline in the milking machine of simultaneous action on: *a* – the rate of milk discharge Q_M and working pressure of the vacuum system P; *b* – pulsation frequency ζ and phase $A+B$



a *b*

Fig. 19. Theoretical and experimental dependences of changes in the fluctuation of vacuummetric pressure ΔP in a lower milk pipeline in the milking machine of simultaneous action on: *a* – the rate of milk discharge Q_M and working pressure of the vacuum system P; *b* – pulsation frequency ζ and phase $A+B$

6. Discussion of results of studying the process of moving the milk mixture in the milking machine

In works [6, 8], it is noted that milking equipment is an element that comes into close contact with milk. Its technical parameters influence the effectiveness of the milking process. The advantages of our study over the cited ones are that we investigated the process of moving the milk mixture in the milking machine of various executions.

Thus, at the initial stage, numerical modeling of the process of moving the milk mixture in the milking machine was carried out. During the study, a pulse chart of vacuummetric pressure P in the inter-wall space of milking cups and milk flow during the period of discharge $Q_{G(\text{A-A})}$ was obtained (Fig. 3).

As a result of our numerical modeling of the process of moving the milk mixture in the milking machine of simultaneous action in an upper milk pipeline, the distribution of the fluid content $1-\alpha$ along the length of the milk hose was established (Fig. 4). These results were also obtained for the apparatus of simultaneous action with a lower milk pipeline (Fig. 8).

Using the Mathematica software package, by the least-square method, we approximated the data obtained according to the selected experiment plan; a mathematical model was built of the relationship of fluctuation (standard deviation) of vacuummetric pressure with factors of numerical modeling.

At the next stage, experimental studies of the process of moving the milk mixture in the milking machine were carried out. Thus, according to the devised methodology, in each experiment, the dynamics of vacuummetric pressure at three points of the milking machine were obtained: a pulsator, a collector, and a milk tap.

It is established that for the variant with an upper milk pipeline, the mode of flow of the milk-air mixture is distributive with an instant switch to intermittent flow (a cork of liquid is formed). For the variant with a lower milk pipeline, another mode of flow of the milk-air mixture is observed, namely the separate flow (the liquid and gas move separately, while creating a clear boundary of the section). That is, the use of a lower milk pipeline in milking plants makes it possible to obtain milk without air bubbles.

As regards the adequacy of the mathematical model, our analysis of Fig. 18, 19 reveals that the nature of the theoretical and experimental dependences is the same. At the same time, a high correlation coefficient indicates the adequacy of the devised theoretical models.

Our resulting functional dependences of the influence of hydrodynamic parameters of motion of the milk-air mixture along a milk-conducting line of the milking plant on the stability of the vacuum mode from a practical point of view make it possible to establish rational parameters for the milking machine. These are the value of the pulsation rate ζ and the operating pressure P, at which its performance is greatest.

The established dependences of the pulsation rate ζ and working pressure of the vacuum system P on the rate of milk discharge Q_M could be used in the design of an adaptive milking machine, which changes the regime parameters depending on the speed of milk discharge.

The current research was made possible owing to the use of innovative equipment (Fig. 1). This allowed us to conduct a set of experiments with specific results.

Our studies of the process of moving the milk mixture in the milking machine are consistent with those reported by other authors earlier [21–24] and complement them. A significant difference in the methodological plan of the conducted research was that an opportunity was created to study a wide range of indicators – from technical to technological.

At the same time, due to the extremely large variability of the design parameters of milking equipment, there are difficulties in fully resolving the issue of studying the process of moving the milk-air mixture in the milking machine. This is still an unresolved issue in the general technological link of milk production at dairy plants.

For us, it seems promising to perform studies aimed at establishing the efficiency of machine milking at robotic dairy plants involving the use of various equipment.

7. Conclusions

1. Based on the results of our numerical modeling, a model of the movement along the milking line of the milking machine of a two-phase milk mixture was built. It linked the value of the vacuummetric pressure fluctuation ΔP, the rate of milk discharge Q_M, the pulse rate ζ, and the value of working vacuummetric pressure P. For an upper milk-conducting system, there is a significant fluctuation in vacuummetric pressure $\Delta P=1.02-4.69$ kPa, which exceeds the regulated value (2.5 kPa). For a lower milk-conducting system, the fluctuation of vacuummetric pressure is $\Delta P=0.59-1.84$ kPa.

2. The patterns of change in the value of working pressure P and the frequency of pulsations ζ in the milking machines of simultaneous and pair actions depending on the rate of milk discharge from the udder have been determined.

3. It is established that the maximum deviation of the value of fluctuation of vacuummetric pressure ΔP between the experimental and theoretical data in a given range of factors is 0.81 kPa; the correlation coefficient is 0.92, which indicates the adequacy of the devised models.

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