A scientific hypothesis has been put forward, according to which an increase in the efficiency of using a vacuum system of milking equipment with an upper milk line with mechanical pulsators can be achieved by predicting its residual resource. As well as with the subsequent planning of maintenance and the identification of patterns and dependences characterizing these processes.

As a result of experimental studies of changes in the technical and technological parameters of the vacuum system of milking equipment with an upper milk line with mechanical pulsators, the theoretical dependences obtained with their correlation coefficient r=0.971–0.972 were empirically confirmed. Namely, the magnitude of the working vacuum, the pulsation rate, the ratio of pulsations, and the tension force of the nipple rubber, depending on the time of operation. It was established that after 175 hours of operation of the milking stationary installation, the value of the working vacuum decreased by 4 %, the pulsation frequency – 14 %, the ratio of pulsations – 16 %, and the tension force of nipple rubber – 21 %.

On the basis of the obtained dependences included in the procedure for forecasting the resource of the vacuum system of milk-milking equipment with an upper milk line with mechanical pulsators, the software package «Alt viewer 1.0» was developed. It is designed to display and automatically process the measurement results of the technical and technological parameters of milking equipment using the designed Tester of milking machines, v.2.0. The software performs the following main functions: reading the measurement results from the memory card, decoding them, displaying them in tabular and graphical forms. As well as the calculation of the parameters of pulsations and the formation of a report, forecasting the resource of the nodes of the vacuum system. The program also provides for the storage of information on the calibration coefficients of pressure sensors, air flow meter, as well as the frequency of polling sensors when measuring pulsations and fluctuations of the working vacuum

Keywords: machine milking, milking equipment, vacuum system, pulsation rate, nipple rubber, resource forecasting

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INCREASING ENERGY EFFICIENCY AND ENABLING THE PROCESS OF VACUUM MODE STABILIZATION DURING THE OPERATION OF MILKING EQUIPMENT

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1. Introduction

Timely maintenance and repair of milking equipment are the main conditions for ensuring uninterrupted production in dairy cattle breeding. In order to achieve this, manufacturers of milking equipment must promptly provide services to maintain dairy equipment in good condition. For this purpose, in order to identify malfunctions and deviations from

the specified parameters of operation of milking equipment, a number of technical means have been developed [1, 2].

According to ISO 9001, enterprises for the development and manufacture of milking equipment must monitor and diagnose, as well as perform warranty maintenance of equipment [3].

There is a large selection of milking equipment, which is included in the main configuration of modern flow milking lines. However, the quality of its maintenance and repair remains unsatisfactory [4]. This is due to the fact that not all complexes where the specified equipment is used have the opportunity to carry out the appropriate technical inspection. Thus, this leads to undesirable consequences both in the operation of the equipment itself and in the state of animal health [5].

Thus, the introduction of operational control over the operation of milking equipment for the use of appropriate technical means is the main factor in the development of dairy cattle breeding.

Therefore, research on the development of a procedure for predicting the resource of the vacuum system of milking equipment is relevant.

2. Literature review and problem statement

Milking animals is a technological process in which humans, machines, and animals interact directly. Obtaining a high-quality dairy product depends on each of the elements of this link, which is emphasized in work [6]. So, a person must prepare the animal for milking, that is, perform preparatory operations (washing and wiping the udder, massage, milking the first streams of milk, the use of means for pre-milking udder, etc.). Milking equipment should satisfy the physiological characteristics and needs of animals, fully stimulate the reflex of milk yield. Along with this, it is necessary to work at the optimal pulsation rate, which is comfortable for the animal. The rigidity of the nipple rubber should correspond to the physiological characteristics of animals, which is emphasized in work [7]. In turn, the animal must be in comfortable microclimate conditions, as well as have a balanced high-quality diet.

As noted in work [8], the production of high-quality milk involves a living organism (a cow). This requires constant monitoring of the efficiency of the milking equipment because it affects the animal's body during the milking process.

In [9], as a result of the analysis of factors causing consequences, four main groups were identified:

– factors characterizing the selection and preparation of cattle for machine milking (selection according to the suitability of cattle for machine milking, training for machine milking, causing a full-fledged milk yield reflex);

– factors characterizing the condition and reliability of the operation of milking equipment. This is the correctness of the installation works, the automation of the shutdown of milking machines, the stabilization of the vacuum mode, the stable supply of the vacuum pump. Along with this, it is also the tightness and contamination of the milk-vacuum line, the load on the milking operator, and the number of milking machines served;

– factors characterizing the state and reliability of the functioning of milking machines (completeness, stability of the pulsation rate and the ratio of cycles, the standard mass of the suspension part, the integrity and tightness of nipple rubber);

– organizational and technological factors of the machine milking process (compliance with the rules of machine milking, the procedure for milking cows).

Along with this, the issue of forecasting the resource of the vacuum system of milking equipment, which involves the development of an appropriate procedure, needs to be clarified.

In work [10], it is noted that the consequences of the use of milking equipment that does not meet the basic requirements (zootechnical, sanitary and hygienic, technical, and technological) are a significant impact on the microstructure of milk and the physiological state of dairy cattle. Thus, the deviation of the above parameters from the regulated zootechnical requirements is characterized as the failure of milking equipment. But, in [10], the issue of the functioning of the vacuum system is not considered.

In [11], it is noted that for an animal, the failure of a vacuum line is more dangerous than the failure of the milking machine. The failure of one or even two milking machines reduces only the efficiency of their use while the failure of the vacuum line leads to a stop in the process of machine milking. It has been established that the failure of milking machines entails the failure of the vacuum line [12].

In works [11, 12] the question of the long-term functioning of the vacuum system of milking equipment, which involves the conduct of appropriate research, is not fully disclosed.

During the operation of milking machines, the air sucked through the pulsator, collector, and teat cups enters the vacuum pump through the vacuum system. At the same time, due to the pulsator and the collector of the milking machine, a pulsating flow of air is created at the outlet, which enters the vacuum line through a vacuum hose [13]. Due to the failure of the milking machine (going beyond the permissible values of the pulsation frequency and the ratio of cycles), the vacuum fluctuations in the vacuum line increase significantly and go beyond the permissible values. This violates the mode of operation of milking equipment and adversely affects the animal's body. Along with this, the question of how exactly this impact occurs and what should be the optimal technical and technological parameters of the equipment are not disclosed.

Studies in [14] have shown that the restoration of normal technical parameters of the milking equipment after their short-term violation does not lead to the mandatory restoration of the physiological state of cattle. In these cases, they often get udder injuries. The onset of such diseases occurs covertly and is detected only after the disease is already clearly expressed. Therefore, in order to prevent the disease of cattle, it is very important not to allow even short-term violations of the parameters at which milking equipment should work.

In study [15] it was established that work on milking equipment with impaired parameters leads to inhibition of the milk yield reflex in an animal, and this leads to severe udder disease and to the culling of cows. Also, in [16], there are data on the influence of the mode of operation of milking equipment on the animal's body, its productivity, milking speed, etc. In works [15, 16], the issue of forecasting the resource of milking equipment, which is in demand during the relevant research, is not disclosed.

The milking machine, directly affecting the mammary gland, plays an important role in regulating the milk yield reflex [17]. From the analysis of that work, it follows that the pulsation rate should be in the range of 50–65 min^{-1}, and the ratio of pulsation cycles should be 0.5–0.7, which is confirmed by the requirements of the international standard ISO 5707. Violations of the optimal parameters of the milking machine in the process of milking are classified as gradual failures of milking equipment.

The authors of works [18, 19] believe that the most negative effects on the body of cattle are caused by increased rigidity of the nipple rubber and insufficient tension in the teat cup. Changing the technical condition of the nipple rubber with a deviation from the permissible values will lead to a gradual failure of the milking equipment. From the analysis of the work, it follows that the tension force of the nipple rubber should be in the range of 50–70 N. But this issue needs to be clarified in terms of the timing of the use of rubber products.

Thus, solving the problem of increasing the efficiency of the machine milking process requires research, refinement, and development of a methodology for predicting the resource of the vacuum system of milking equipment.

3. The aim and objectives of the study

The aim of this study is to increase energy efficiency and ensure the process of stabilization of the vacuum regime during the operation of milking equipment. This will make it possible to increase the efficiency of operation of the vacuum system of milking equipment with an upper milk line with mechanical pulsators.

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

– to determine the influence of technical and technological parameters of the vacuum system of milking equipment on the efficiency of machine milking;

– to develop a methodology for predicting the resource of the vacuum system of milking equipment.

4. The study materials and methods

4. 1. The relationship of technical and technological parameters of the vacuum system of the milking machine

The hypothesis of the study assumes that increasing the efficiency of the vacuum system of the milking machine can be achieved by predicting its residual resource, followed by maintenance planning.

The vacuum system of the milking machine is represented in the form of interrelated nodal elements (Fig. 1). It consists of a vacuum pump, which is connected in series to a vacuum cylinder, a vacuum regulator using a vacuum duct. In parallel, milking machines are connected to the vacuum wire, which consist of a pulsator, a vacuum hose, a collector, and four teat cups. The pulsator and the collector can be combined into a single node – the pulse collector. Each of the given nodal elements is characterized by appropriate technical and technological parameters.

The criterion for evaluating the technological process of machine milking is the speed of milk yield. It is influenced by the physiological parameters of the cow (udder girth, udder depth, milk pressure in the udder tank, one-time milk yield, etc.) and the technical and technological parameters of the vacuum system of the milking machine [20].

4. 2. Procedure of experimental studies of changes in the technical and technological parameters of the milking machine with the upper milk line with mechanical pulsators during its operation

Studies of the vacuum system of the milking machine were carried out at a laboratory bench (Fig. 2).

The motor was controlled using the Danfoss frequency converter (Denmark), which served as a time relay. Periodic shutdown and switching on of the electric motor were carried out according to the following parameters – 0.5/2 hours. This control can be programmed using the built-in timer, which will increase the rotational speed to the required value in the first period of time and decrease to 0 in the second period of time. Thus, the function of the time relay is carried out.

The research was carried out using the plate-rotary vacuum pump UVU-60/45 (blades – textolite), the pulsator of the two-stroke milking machine «Maiga» (Ukraine), and the nipple rubber DD.041 A (Ukraine).

The pump was taken as an example of checking the developed procedure and a tester of milking machines. The choice for experiments is justified by the fact that it has the largest number of failures, which makes it possible to obtain data at a fast pace (without waiting for 1–3 years of operation).

The technical and technological parameters of the vacuum system of the milking machine (working pressure, ratio and frequency of pulsation cycles) were determined using the tester of milking machines TDU v.2 (DDAEU, Ukraine) in accordance with the international standard ISO 6690.

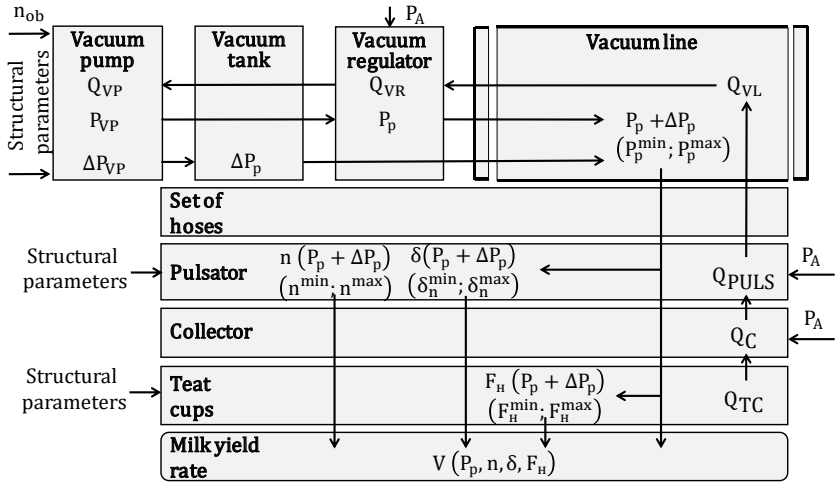


Fig. 1. The relationship of technical and technological parameters of the vacuum system of the milking machine: V – the speed of milk yield of the animal; Q – air costs; P – vacuum pressure; ΔP – fluctuations (changes) of vacuum; F_H – rubber tension force; Δ – ratio of pulsations; n – pulsation rate; VP – vacuum pump; VR – vacuum regulator; VL – vacuum line; $PULS$ – pulsator; C – collector; TC – teat cups; p – working; max – largest; min – lowest; A – atmospheric

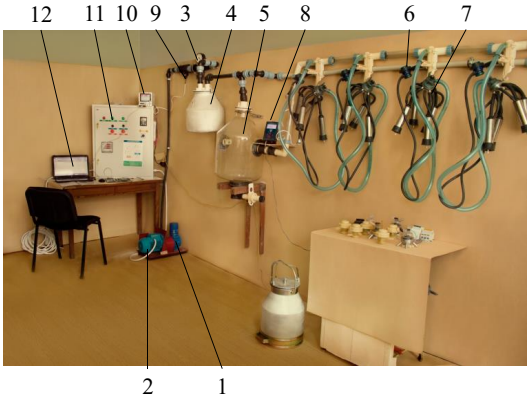


Fig. 2. General view of the of the vacuum system of the milking machine with the upper milk line with mechanical pulsators: 1 — vacuum pump; 2 — electric motor; 3 — vacuum regulator and vacuum gauge; 4 — vacuum cylinder; 5 — milk collector; 6 — pulsator; 7 — suspension part of the milking machine; 8 — a set of instrument equipment for parameter control; 9 — air flow sensor BOSCH 280 218 037, which is connected to the videographic recorder Ecograf-T; 10 — video recorder Ecograf-T; 11 — control unit of the electric motor Danfoss (Denmark); 12 — personal computer

Using the PCE FG 200 dynamometer (Germany), the tension force of the nipple rubber was determined in accordance with GOST 270-75. The measurement error was 0.01 N.

In accordance with the observation plan [N, $R(r, T)$], patterns of change in the technical and technological parameters of the vacuum system of milking machines depending on the duration of its operation were determined. The specified research plan provides for the simultaneous testing of N objects. In the case of failure of the object, it is replaced with a new one. Observations are stopped if the number of failures r is reached or when the working time T expires.

To conduct experimental studies, the number of objects of observation was calculated by the formula:

$$N = \chi \cdot \frac{\overline{t_0}}{t_k}, \quad (1)$$

where χ is the tabular coefficient, t_0 is the average operating time per failure, t_k is the duration of observations.

As a result of the calculation, it was established that the number of observation objects for the planned research is 10.

The influence of the technical condition of the milking machine on the technical and technological parameters of its nodal elements was represented in the form of a mathematical model – regression equations:

$$C = \sum_{i=0}^{n} a_i \cdot t^i, \quad (2)$$

where a_i – regression coefficients, t – duration of operation, y – technical technological parameter of the vacuum system of the milking machine.

Studies were carried out at the following parameters y: pulsation cycle frequency n, min^{-1}, the ratio of pulsation cycles Δ, the working vacuum of the vacuum system P, kPa, the tension force of the nipple rubber F_H, N.

5. Results of improving energy efficiency and ensuring the process of stabilization of the vacuum mode during the operation of milking equipment

5. 1. Results of determining the influence of technical and technological parameters of the vacuum system of milking equipment on the efficiency of machine milking

Before the launch of the laboratory bench, rational technical and technological parameters were established:

$$P = 50.6 \text{ kPa}; \; n = 55.9 \text{ min}^{-1}; \; \delta = 0.58; \; F_H = 64.8 \text{ N};$$

$$V_{max} = 1.52 \text{ l/min}; \; Q_{min} = 2.19 \text{ m}^3/\text{h}. \quad (3)$$

At the next stage, the values of these parameters were recorded every 20 hours of the laboratory bench (Fig. 2).

Having recorded a change in the technical and technological parameters of the vacuum systems of the milking machine during 3000 hours of operation of the laboratory bench, the corresponding patterns were determined:

– working pressure of the vacuum system:

$$P(t) = 6 \cdot 10^{-7} t^2 - 3.9 \cdot 10^{-3} t + 52, \; r = 0.972; \quad (4)$$

– pulsation rate:

$$n(t) = 1 \cdot 10^{-4} t^2 - 7.4 \cdot 10^{-2} t + 60, \; r = 0.978; \quad (5)$$

– the ratio of pulsation cycles:

$$n(t) = 1 \cdot 10^{-6} t^2 - 7.0 \cdot 10^{-4} t + 0.6, \; r = 0.974; \quad (6)$$

– nipple rubber tension forces:

$$F_H(t) = -5 \cdot 10^{-4} t^2 - 1.6 \cdot 10^{-2} t + 60, \; r = 0.971; \quad (7)$$

where r is the correlation coefficient.

Plots of dependences (4) to (7) are shown in Fig. 3.

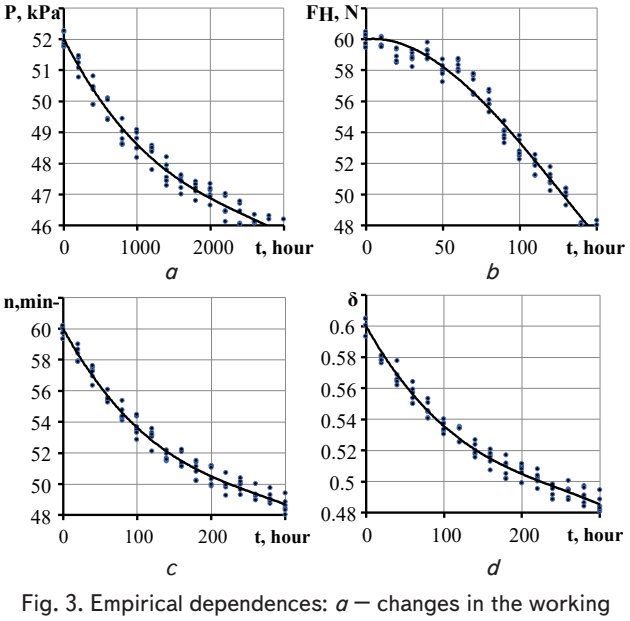


Fig. 3. Empirical dependences: a — changes in the working vacuum P depending on the time of operation t; b — changes in the tension force of the nipple rubber F_H depending on the time of operation t; c — changes in the pulsation frequency n depending on the time of operation t; g — changes in the ratio of cycles Δ depending on the time of operation t

The obtained empirical regularities of changes in the technical and technological parameters of the vacuum system of the milking machine make it possible to determine its technical condition at any time. It was found that on hour 175 of the operation of the vacuum system, the value of the working vacuum decreased by 4 %. In turn, the pulsation frequency – by 14 %, the ratio of pulsations – by 16 %, and the tension force of nipple rubber – by 21 %.

Thus, increasing the efficiency of operation of the vacuum system of the milking machine is possible thru the introduction of periodic technical diagnostics with a certain time interval.

5. 2. Development of a procedure for forecasting the resource of the vacuum system of milking equipment

Based on the results of our research, a methodology for predicting the resource of the vacuum system of the milking machine has been developed.

The initial data for forecasting the resource of the vacuum system of the milking machine are the dynamics of changes in its technical and technological parameters (4) to (7). Based on the forecast obtained, it is possible to carry out maintenance and repair planning.

Our studies indicate the need for daily technical diagnostics of milking equipment in order to identify deviations of its technical and technological parameters from the permissible values and to predict the resource of its components. Fig. 4 shows changes in technical and technological parameters depending on the duration of operation of the vacuum system after the introduction of the developed procedure of resource forecasting. Dotted line – a change in a parameter during traditional maintenance. Solid line – a change in a parameter after the introduction of the developed procedure of resource forecasting.

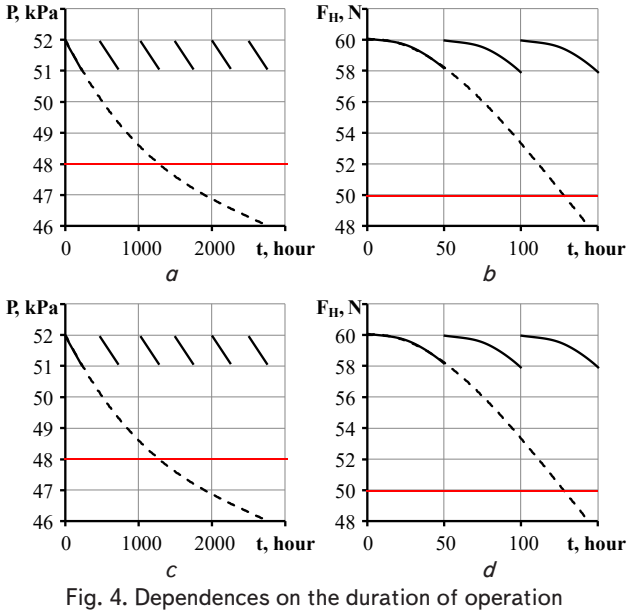


Fig. 4. Dependences on the duration of operation of the vacuum system t after the introduction of the resource forecasting procedure: a – changes in the working vacuum P; b – changes in the tension force of nipple rubber F_H; c – changes in the frequency of pulsations n; g – changes in the ratio of cycles of pulsations Δ

Analysis of failures of the nodal elements of the vacuum system of the milking machine made it possible to conclude that machine milking should occur under a stable vacuum mode of 48.0–52.0 kPa; pulsation rate, 50–65 min^{-1}; the ratio of pulsation cycles, 0.5–0.7; the tension force of nipple rubber, 50–70 N.

Based on the obtained patterns (4) to (7), which were included in the methodology for predicting the resource of the vacuum system of the milking machine, the software package «Alt viewer 1.0» was developed. It is intended for displaying and automatic processing of measurement results of technical and technological parameters of milking equipment using the developed Tester of milking machines v. 2.0 (Fig. 5).

Fig. 5. Milking machine tester v. 2.0

The software performs the following main functions: reading measurement results from a memory card, decoding them, displaying them in tabular and graphical forms, calculating the parameters of pulsations and generating a report, as well as predicting the resource of vacuum system nodes.

The main window of the program (Fig. 6, *a*) is divided into 4 parts (widgets):

– widget 1 is designed to display a list of measurements made in the form of a hierarchical structure containing data on the date they were carried out. As well as measured values (working pressure of the vacuum system, pulsation, pressure fluctuation, and air flow), and the number of the node of the milking machine to which the sensors were connected;

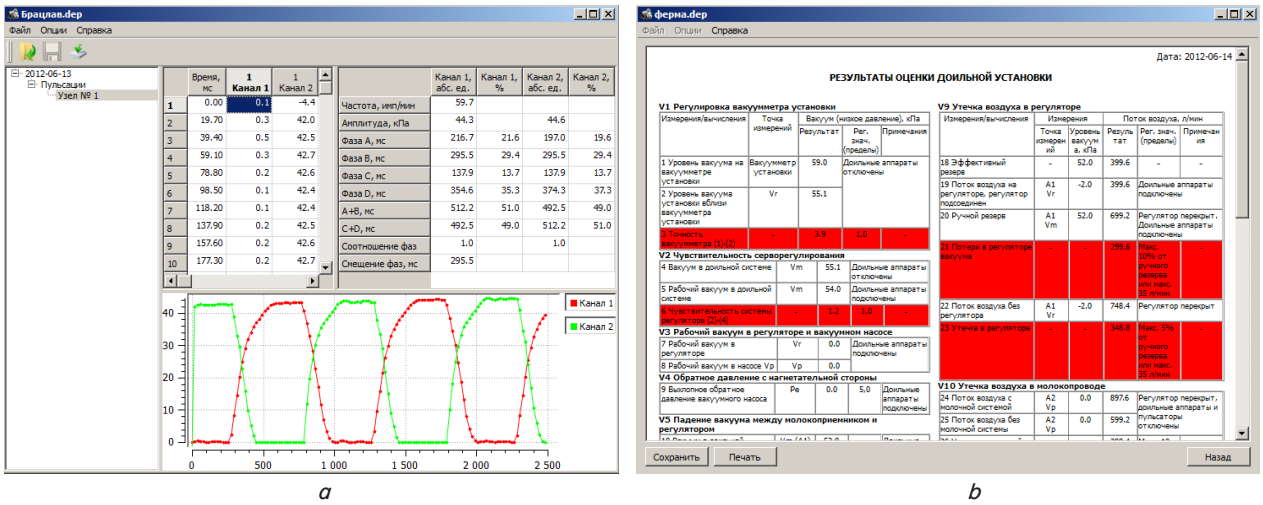
– widget 2 displays the results of one or more parallel measurements in tabular form, taking into account the calibration coefficients of the sensors used;

– widget 3 displays the results of calculating the parameters of pulsations of vacuum-metric pressure (amplitude, frequency, balance of pulsation phases, duration of pulsation phases in milliseconds and as a percentage);

– widget 4 is designed to display the time dependence of pressure pulsations in two channels.

The software also provides for the storage of information on the calibration coefficients of pressure sensors, air flow meter, as well as on the frequency of polling sensors when measuring pulsations and fluctuations of the working vacuum. Viewing and changing the current calibration coefficients is carried out using a separate dialog box.

Measurement results recorded on a memory card can be stored on a computer in a database that has its own format. The software enables to create new databases, enter the measurement results read from the memory card into the existing databases, as well as display, process, and delete data.



a *b*

Fig. 6. Alt viewer 1.0 software appearance: *a* — main window; *b* — ISO 6690 report

To ensure the possibility of evaluating the milking equipment, the testing of which was carried out, the program automatically generates a report in the form of a summary table. It includes the main results of measurements, calculations of technical and technological parameters in accordance with the ISO 6690 standard, and the calculated residual life of milking equipment units (Fig. 6, *b*).

6. Discussion of results of improving energy efficiency and ensuring the process of stabilization of the vacuum regime during the operation of milking equipment

The efficiency and energy intensity of the milking process depend on the operation of the vacuum system of milking equipment [21].

In work [22] it is noted that during milking, milking equipment comes into contact with cattle. The technical and technological parameters of the equipment affect the efficiency of the process of milking. The main advantages of our study over those specified and carried out earlier are the development of a methodology for predicting the resource of the vacuum system of milking equipment.

Thus, at the initial stage, changes in technical and technological parameters were investigated depending on the duration of operation of the milking equipment. Empirical dependences of changes in the technical and technological parameters of the vacuum system of milking equipment are derived (Fig. 3).

As a result of the analysis of the impact of failures of milking equipment on the efficiency of the machine milking process, the main parameters were established on which the effectiveness of the interaction between the animal and machine depends. This is the amount of vacuum (18 %), the pulsation rate of the milking machine (14 %), the ratio of pulsation cycles of the milking machine (14 %), the tension force of nipple rubber in a teat cup (16 %).

At the next stage, on the basis of the research, a methodology for predicting the resource of the vacuum system of milking equipment was developed. Dependences on the duration of operation of the vacuum system after the introduction of the procedure were built (Fig. 4). By analyzing them, it can be stated that machine milking should occur under a constant vacuum mode of 48.0–52.0 kPa, a pulsation rates of 50–65 min^{-1}, the ratio of pulsation cycles of 0.5–0.7, the tension force of nipple rubber of 50–70 N.

Subsequently, the software package «Alt viewer 1.0» was developed, designed to display and automatically process the measurement results of the technical and technological parameters of milking equipment. This became possible with the use of the developed Tester of milking machines v. 2.0 (Fig. 5). This has allowed us to carry out a set of experiments with prompt and reliable obtaining of specific results.

The results of our research are consistent with those reported by the authors of [23–26], carried out earlier, and complement them. A significant difference in the methodological plan of the research was that a real possibility of measuring the main technical and technological parameters of milking equipment was created.

Along with this, due to the extremely large variability of the design parameters of milking equipment, there are difficulties in fully resolving the issue of predicting the resource of the vacuum system. This is still an unresolved issue in the general technical and technological link of milk production.

Studies aimed at establishing the complex impact of robotic milking technologies on cattle while determining the interaction of individual technical factors of equipment on the process of milking are considered promising.

7. Conclusions

1. As a result of our experimental studies of changes in the technical and technological parameters of the vacuum system of milking equipment with an upper milk line with mechanical pulsators, the theoretical dependences obtained with their correlation coefficient r=0.97 were empirically confirmed. Namely, the magnitude of the working vacuum, the pulse rate, the ratio of pulsations, and the tension force of nipple rubber, depending on the time of operation. It was established that after 175 hours of operation of the milking machine of the UDM type, the value of the working vacuum decreased by 4 %, the pulsation frequency – by 14 %, the ratio of pulsation cycles – by 16 %, the tension force of nipple rubber – by 21 %.

2. A procedure for forecasting the resource of the vacuum system of milking equipment with an upper milk pipeline

with mechanical pulsators of any type, which is included in the created software package «Alt viewer 1.0», has been developed. Its feature is the operational determination of the residual resource of the units of the vacuum system of milking equipment, which makes it possible to carry out their timely repair.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

Manuscript has no related data.

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