

The scientific task to improve energy efficiency and ensure the process of vacuum regime stabilization in the operation of milking machines has been solved.

A mathematical model of the process of functioning of the servo control system of a rotary plate vacuum pump was built; the numerical modeling of its workflow was carried out.

This paper reports the results of experimental studies on the influence of the regime parameters of the rotary plate vacuum pump on the efficiency of its operation, as well as the results of experimental research on the servo control system for the rotary plate vacuum pump.

The operational process of the rotary plate vacuum pump HB-1200 for a milking machine was investigated. The influence of mode parameters (rotor speed n and vacuum pressure P) on the performance of the vacuum pump, Q_a , vacuum pressure fluctuation, ΔP , and the power consumption of the vacuum pump drive, N_p , has been determined.

The servo control system of the rotary plate vacuum pump was experimentally investigated based on the developed algorithms of its operation. In a generally accepted algorithm, vacuum fluctuation increases with increasing an airflow rate: at $\Delta Q_a = 45$ l/min – $\Delta P = 2.3$ kPa; at $\Delta Q_a = 90$ l/min – $\Delta P = 4.6$ kPa; at $\Delta Q_a = 135$ l/min – $\Delta P = 6.4$ kPa. Unlike the generally accepted one, the developed algorithm enables a stable vacuum mode with the largest vacuum fluctuation being $\Delta P = 2.4$ kPa.

For the first time, the functional dependence of the influence of the regime parameters of the rotary plate vacuum pump with its automatic servo control system on the stability of the vacuum regime of a milk-vacuum system in the milking machine was established.

The results can be applied when improving milking machines in terms of ensuring the stabilization process of the vacuum regime

Keywords: milking machine, vacuum pump, vacuum pressure, vacuum fluctuation, servo control

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JUSTIFYING PARAMETERS FOR THE AUTOMATIC SERVO CONTROL SYSTEM OF A ROTARY PLATE VACUUM PUMP IN THE MILKING MACHINE

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1. Introduction

The issues of mechanization of high-quality and energy-saving implementation of technological processes of milk

production remain yet to be fully resolved [1]. This is especially true of technological processes that require accurate execution of regulatory operations that have an impact on productivity, cattle health, and the quality of the resulting

product [2–4]. These processes include milking. There is a wide range of high-performance milking machines with servo control systems for their milk-vacuum systems, the main determining criterion for the effective operation of which is energy consumption.

The vacuum pressure in the milking machine is maintained by the operation of the vacuum pump, which compensates for the flow of air. Since these flows are unstable, and the vacuum pump operates under a stationary mode, vacuum regulators are used in most milking machines. They are differential valves that open if the difference between external and internal pressures exceeds the permissible limit [5, 6]. Thus, energy is spent on the operation of the vacuum regulator inefficiently. Thus, the process of stabilization of the vacuum regime of the milking machine is achieved by increasing the volume of the vacuum cylinder and, as a result, increasing the performance of vacuum pumps. However, this causes an increase in the power consumed by the milking machine. The solution to this problem is the use of a servo control system for the vacuum mode of the milking machine.

One of the drawbacks of installations with servo control systems is non-stationary fluctuations in the vacuum regime, which, according to zootechnical and international technical and technological requirements, lead to a significant technological impact on the microstructure of milk and the physiological state of cattle [7].

Therefore, improving the efficiency of the operation of milking machines by stabilizing the vacuum regime is of national economic importance and is a relevant task.

2. Literature review and problem statement

As noted in [8], the intensification of milk production by increasing the productivity of cattle imposes stricter requirements for compliance with zootechnical and technological requirements for milking cows. Highly productive cattle species are most sensitive to violations of milking technology, which leads to diseases of the udder and, as a result, a decrease in productivity, culling, and significant economic losses.

In [9], it is noted that various milking machines are used for milking cows. The choice of the type of milking machine depends on the size of the farm, the productivity of cattle, the technique of their maintenance, and climatic conditions. However, at the same time, the optimal technical and technological values of the vacuum system of the equipment are not determined.

In [10], it is noted that the modern milking machine operates on a variable vacuum created by a vacuum pump. The main task of the vacuum pump is to create a vacuum in the system of interconnected pipelines and devices for creating, measuring, and regulating the operation of the milking machine. Along with this, the parameters of the automatic servo control system of the rotary plate vacuum pump of the milking machine are not established or substantiated.

Thus, the base of any milking machine is a vacuum pump, which creates the necessary vacuum in the vacuum system. The performance of the milking machine, its reliability, and noise level depend on the vacuum pump. There are a significant number of different vacuum pumps in the market, which allows one to improve the old and develop new milking machines based on them, which is indicated in [11, 12].

To enable the efficient operation of the milking machine, it is necessary to maintain the vacuum level in the milk and

vacuum systems at a constant level. In addition, as indicated in work [13], the movement of milk from milking machines through the milking system to the milk collectors requires the necessary flow of air, which must vary depending on the load. Measurement of these parameters at different nodes and points of the milking machine is a necessary point for a rational vacuum in the system [14]. A stable vacuum can be achieved by using a servo control system of vacuum pumps.

The analysis of the condition of milking equipment [15] showed that the system for providing servo control of vacuum pumps should solve the following tasks:

- measure the level of vacuum pressure and air flow rate in the vacuum system of the milking machine;
- control the level of vacuum pressure and air flow rate in the vacuum system of the milking machine.

In accordance with ISO 6690, the control systems and performance of the vacuum pump after the starting period must provide a working vacuum level with deviations within ± 2.5 kPa from the rated value. To effectively regulate the performance of the installed vacuum pump, the adjustment losses should not exceed 35 l/min for atmospheric air or 10 % manual reserve, depending on which parameter is higher [16].

However, the cited papers [15, 16] do not fully define the expediency of using an automated servo control system of a rotary plate vacuum pump and, in accordance with this, ways to address it.

Thus, as indicated in work [17], the option of overcoming the corresponding difficulties regarding the feasibility of using an automated servo control system of a rotary plate vacuum pump is to conduct appropriate research.

In order to eliminate various violations in the control of machine milking and obtain high yields, it is necessary to substantiate the parameters of the automatic servo control system of the vacuum pump of the milking machine [18].

Thus, tackling the task of increasing the efficiency of machine milking requires research, refinement, and improvement of key provisions and elements of an automatic servo control system, which are of both scientific and practical interest.

3. The aim and objectives of the study

The purpose of this study is to substantiate the parameters for the automatic servo control system of the rotary plate vacuum pump of the milking machine. This will make it possible to increase energy efficiency and enable the process of stabilization of the vacuum regime during the operation of milking equipment.

To achieve the set aim, the following tasks have been solved:

- to develop a technological scheme and principle of operation of the servo control system of rotary plate vacuum pumps;
- to investigate the influence of the regime parameters of the rotary plate vacuum pump on the efficiency of its operation;
- to experimentally investigate the servo control system of rotary plate vacuum pump based on the developed algorithms of its operation.

4. The study materials and methods

Experimental studies were carried out on an experimental bench (Fig. 1, *a*) designed according to the technological scheme (Fig. 1, *b*).

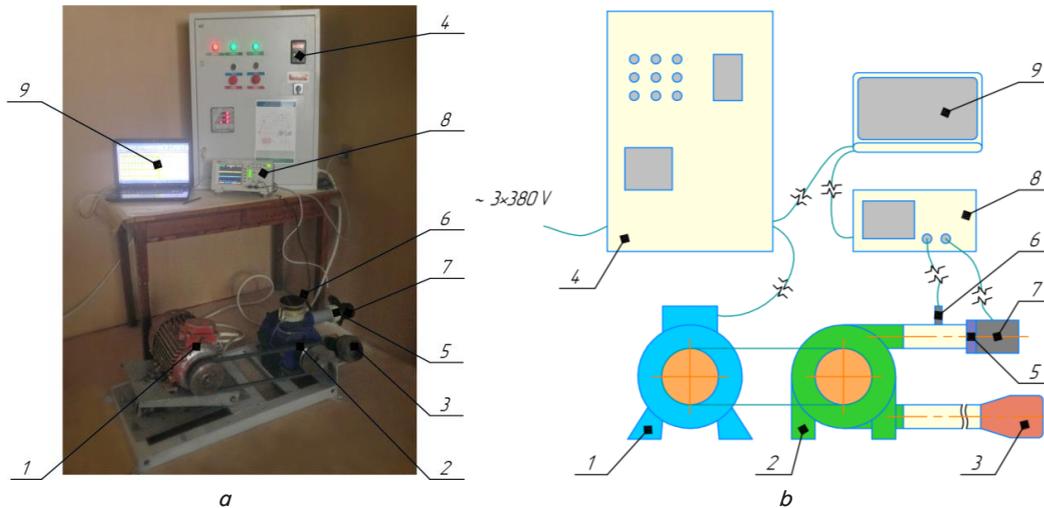


Fig. 1. Experimental bench to study the designed vacuum pump HB-1200: *a* – general view; *b* – technological scheme: 1 – induction electric motor; 2 – experimental sample of the rotary plate vacuum pump HB-1200 (Ukraine); 3 – muffler; 4 – frequency regulator Danfoss VLT MicroDrive (Germany); 5 – air flow rate regulator; 6 – pressure sensor MPX5100D (Netherlands); 7 – air flow rate sensor BOSCH 0 280 218 037 (Germany); 8 – RIGOL DS1022C oscilloscope (People’s Republic of China); 9 – personal computer

To control and change the speed of the vacuum pump rotor, the Danfoss VLT MicroDrive (Germany) electric frequency converter was used.

The value of the vacuum pressure was determined by using the air flow rate regulator (by changing the inlet area S , mm^2) and controlled by using the pressure sensor MPX5100D (Netherlands). Pump performance was measured using the BOSCH 0 280 218 037 air flow rate sensor (Germany).

The power consumption of the vacuum pump drive was measured by Danfoss VLT MicroDrive (Germany).

Data from pressure sensor MPX5100D and air flow rate sensor BOSCH 0 280 218 037 were recorded on the RIGOL DS1022C oscilloscope (People’s Republic of China) and transmitted to a personal computer.

Studies on determining the dependence of the influence of the technical parameters of the vacuum pump on the efficiency of its operation were carried out using the method of mathematical planning of a passive two-factor experiment.

Studies of the influence of the regime parameters of the rotary vane vacuum pump on the efficiency of its operation were carried out according to two factors: rotor speed n , rpm, and the value of the vacuum pressure P , kPa.

The output variables were the performance of the vacuum pump Q_a , m^3/h , the power consumption of the vacuum pump drive N_p , kW, and vacuum fluctuation ΔP , kPa.

The limits of variations of factors were selected from theoretical studies of the structural and technological parameters of the rotary plate vacuum pump and previous studies. The matrix for planning a passive experiment is given in Table 1.

Based on our results, it is necessary to develop an algorithm for the servo control system of the rotary plate vacuum pump and check its functionality by simulating the process of connecting or disconnecting the milking machines to the milk-vacuum system.

At the beginning of the research, on the air flow rate regulator (Fig. 1), the initial value of 400 l/min is set, which corresponds to the air flow rate of the milking machine with the milking machines turned off.

Table 1

Experiment planning matrix

No.	n, min^{-1}	S, mm^2	P, kPa
1	600	0	61.8
2	1,200	0	75.9
3	1,800	0	85.7
4	2,400	0	89.0
5	3,000	0	90.0
6	600	55	47.7
7	1,200	55	61.8
8	1,800	55	71.6
9	2,400	55	75.9
10	3,000	55	75.9
11	600	118	29.2
12	1,200	118	45.5
13	1,800	118	59.6
14	2,400	118	64.0
15	3,000	118	65.1
16	600	181	12.9
17	1,200	181	23.8
18	1,800	181	31.4
19	2,400	181	37.9
20	3,000	181	42.3
21	600	243	5.9
22	1,200	243	16.2
23	1,800	243	23.8
24	2,400	243	28.1
25	3,000	306	3.7
26	600	306	11.8
27	1,200	306	16.2
28	1,800	306	20.5
29	2,400	306	22.7
30	3,000	368	1.0
31	600	368	8.6
32	1,200	368	11.8
33	1,800	368	16.2
34	2,400	368	17.3
35	3,000	306	3.7

In the process of our research, with an interval of 10 s, the position of the air flow rate regulator changes, both by increasing and reducing air consumption by the values of 45 l/min, 90 l/min, and 135 l/min.

The criterion for assessing the efficiency of the servo control system algorithm of the rotary plate vacuum pump is the vacuum fluctuation ΔP and the power of its drive N_p .

5. Results of justifying the expediency of using an automated servo control system of rotary plate vacuum pump

5.1. Developing a technological scheme and the principle of operation of the servo control system of rotary plate vacuum pumps

To solve the task of controlling the level of vacuum pressure of the vacuum system of the milking machine, a technological scheme of the servo control system of the rotary plate vacuum pump was developed (Fig. 2). It includes a frequency converter, an induction electric motor, a rotary plate vacuum pump, vacuum pressure sensors, and a vacuum system. It, in turn, consists of various air ducts and tanks, such as vacuum cylinders, a milk collector, pulsators, vacuum hoses, collectors, and teat cups.

The servo control system of the rotary plate vacuum pump of the milking machine works as follows (Fig. 2). The desired level of vacuum pressure P_n is set on the converter of the rotational speed of an induction electric motor, which must be maintained in the vacuum system. As a result of the change in the air flow rate Q_a of the vacuum system by ΔQ_a , the vacuum pressure P in it changes. From the vacuum pressure sensor, which is installed in the vacuum system, the current pressure value P is sent to the frequency converter. If the current value P is greater than the desired P_n , then the frequency converter reduces the rotational speed n of the shaft of the induction electric motor (Fig. 3, a); otherwise, increases it (Fig. 3, b).

With an increase (decrease) in the shaft speed of an induction electric motor, the rotational speed of the rotor of the rotary vane vacuum pump increases (decreases), which leads to an increase (decrease) in its performance. Thus, the vacuum pressure P is equalized to the desired value P_n .

The use of the proposed system could reduce the energy consumption of the vacuum pump of the milking machine and stabilize the vacuum pressure in the vacuum system.

Our analysis of Fig. 3 revealed that in order to enable the same mode of control of vacuum pressure in the vacuum system of the milking machine, it is necessary that the rate of its change is the same with increasing and decreasing the rotational speed of the vacuum pump rotor.

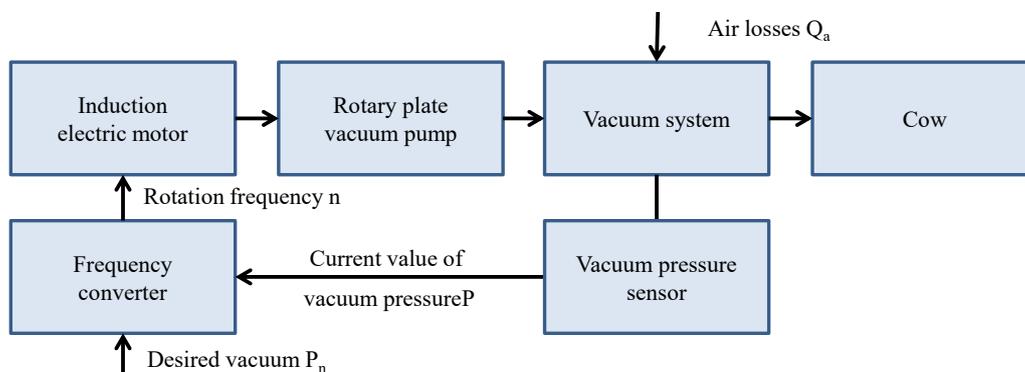


Fig. 2. Technological scheme of a servo control system of the rotary plate vacuum pump of a milking machine

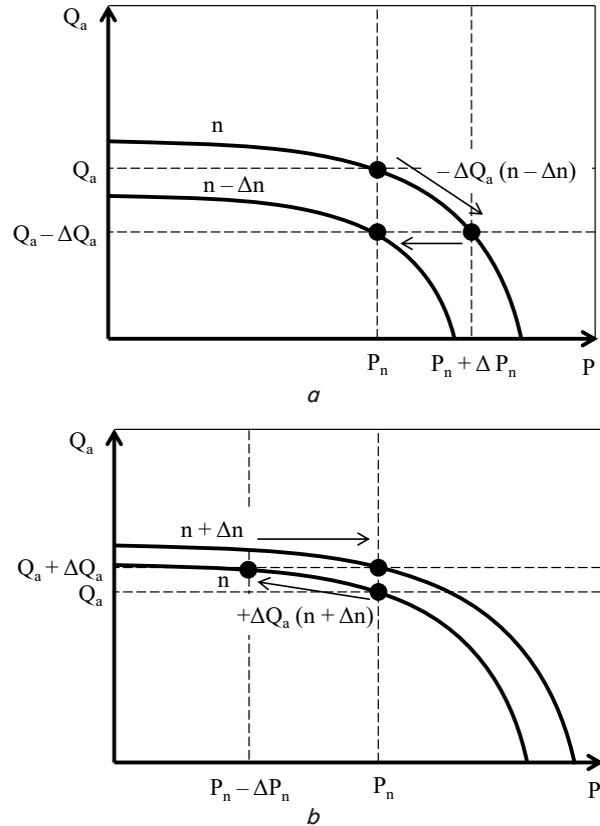


Fig. 3. Changing the mode parameters of the rotary plate vacuum pump during the operation of the servo control system: a – reducing the rotational speed; b – increasing the rotational speed

To meet the accepted condition, it is necessary that the regime parameters of the rotary plate vacuum pump obey the equation:

$$\frac{\Delta Q_a(P_n, n + \Delta n)}{\Delta P} = \frac{\Delta Q_a(P_n, n - \Delta n)}{\Delta P}, \quad (1)$$

where P_n is the given vacuum pressure in the vacuum system, Pa, ΔQ_a is the change in the air flow rate in the system, l/min.

The coefficients of dependence $Q_a(P, n)$ are influenced by the design parameters of the rotary plate vacuum pump [19]. Solving equation (1) will make it possible to determine their rational values at which the proposed servo control system is most effective.

5. 2. Investigating the influence of the regime parameters of the rotary plate vacuum pump on the efficiency of its operation

As a result of collecting data from the pressure sensor during various experiments, the dynamics of changes in vacuum pressure were established depending on the rotor speed and air flow rate of the vacuum pump.

For each experiment, the average value and standard deviation (fluctuation) of vacuum pressure were calculated and mathematical models of the technological process of creating a vacuum by a rotary plate vacuum pump HB-1200 were constructed.

According to the research results, a mathematical model of the influence of the studied factors on the performance of a vacuum pump was built. The resulting mathematical model is as follows:

$$Q_a = 44.5436 + 0.426725n - 1.56184P + 0.16936P^2 - 0.00266467P^3, \tag{2}$$

where Q_a is the vacuum pump performance, l/min, n is the rotor speed, rpm, P is the vacuum pressure, kPa.

According to the calculated values of the correlation coefficient of 0.97, the model is adequate at a given level of confidence probability (0.95).

Analyzing equation (2), it can be argued that the performance of the developed vacuum pump is influenced by all the above factors. The graphical interpretation of dependence (2) is shown in Fig. 4.

Fig. 4 shows that at a certain value of the rotational speed of the rotor of the vacuum pump, the productivity increases with a drop in vacuum pressure in the region from 50 to 90 kPa. Further, in the region from 0 to 50 kPa, the performance is leveled to the maximum value, which is linearly dependent on the rotational speed.

For the fluctuation of vacuum pressure, a mathematical model of the influence of the factors under study was built (Fig. 5):

$$\Delta P = 0.087207 - 0.0000167177n + 0.104101P - 0.0000152404nP, \tag{3}$$

where ΔP is the vacuum pressure fluctuation, kPa.

According to the calculated values of the correlation coefficient of 0.93, the model is adequate at a given level of confidence probability (0.95).

Analyzing Fig. 5, it was found that with an increase in vacuum pressure, its fluctuation also increases, and with an increase in rotational speed, the fluctuation fades away. This is due to the rate of change in the volume of the working chamber of the rotary vacuum pump.

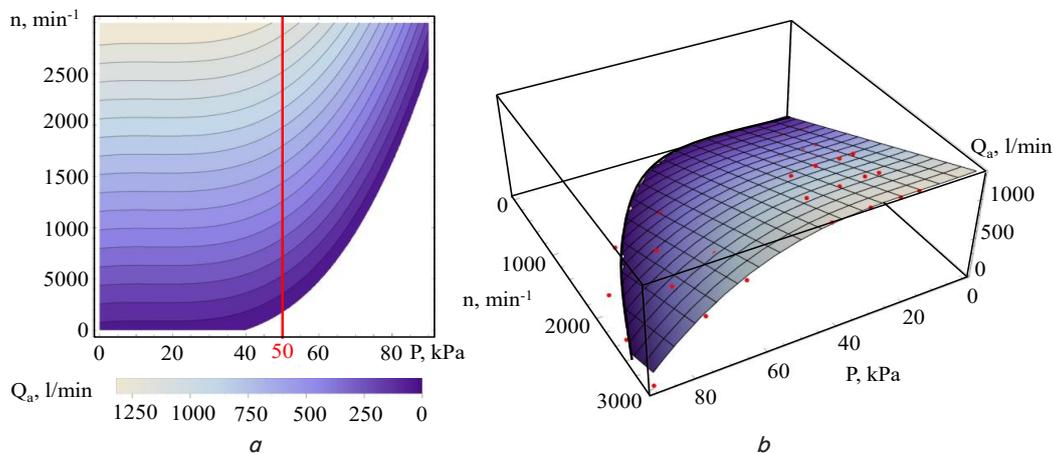


Fig. 4. The influence of rotor speed n and vacuum pressure P on vacuum pump performance Q_a : a – contour plot; b – three-dimensional plot

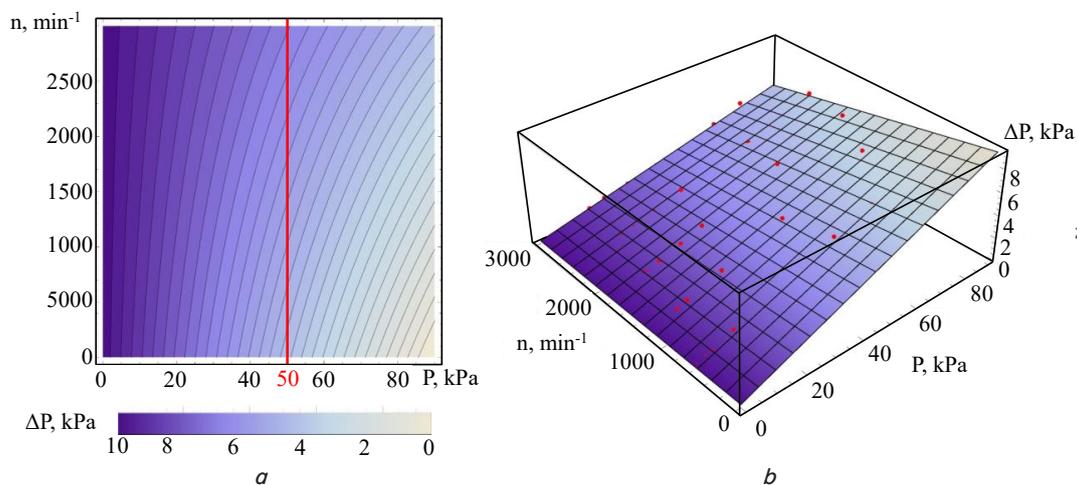


Fig. 5. The influence of rotor speed n and vacuum pressure value P on vacuum pressure fluctuation ΔP : a – contour plot; b – three-dimensional plot

The resulting mathematical model of the influence of the studied factors on the power consumption of the vacuum pump drive takes the following form (Fig. 6):

$$N_p = -1.78081 + 0.003086n + 0.01963P - 3.71 \cdot 10^{-6}nP, \quad (4)$$

where N_p is the vacuum pump drive power consumption, kW.

According to the calculated values of the correlation coefficient of 0.94, the model is adequate at a given level of confidence probability (0.95).

Our analysis of dependence (4) and its graphical interpretation (Fig. 6) showed that the factors under study influence the power consumption of the vacuum pump drive linearly. Moreover, the change in rotational speed has a greater effect on power at vacuum pressure from 40 to 90 kPa.

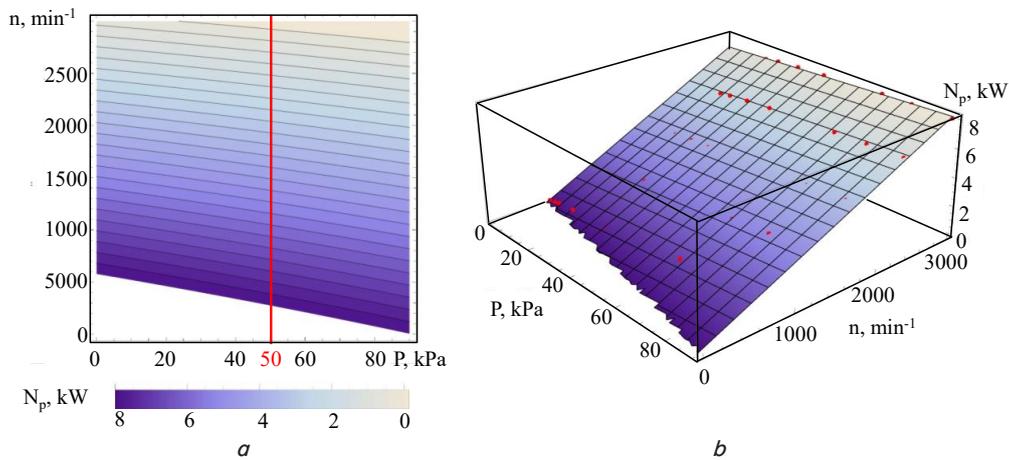


Fig. 6. The influence of rotor speed n and vacuum pressure value P on the power consumption of the vacuum pump drive N_p : a – contour plot; b – three-dimensional plot

5.3. Experimental studies of the servo control system of a rotary plate vacuum pump

Modern servo control systems of rotary plate vacuum pumps employ a generally accepted algorithm (Fig. 7), which includes the following steps:

1. Set the values of the given vacuum pressure in the vacuum system P_n and the constant step of variation of the rotor rotational speed of the vacuum pump Δn .
2. Zero vacuum pressure values in the vacuum system $P=0$ and the initial rotational speed of the vacuum pump rotor $n=0$.
3. Measure the vacuum pressure value in the vacuum system P .
4. In case of disconnection of the «Stop» button or emergency system – continue operations, otherwise – zero the rotor speed of the vacuum pump $n=0$; the end of the algorithm execution.
5. Compare the vacuum pressure value in the vacuum system P with the given P_n .

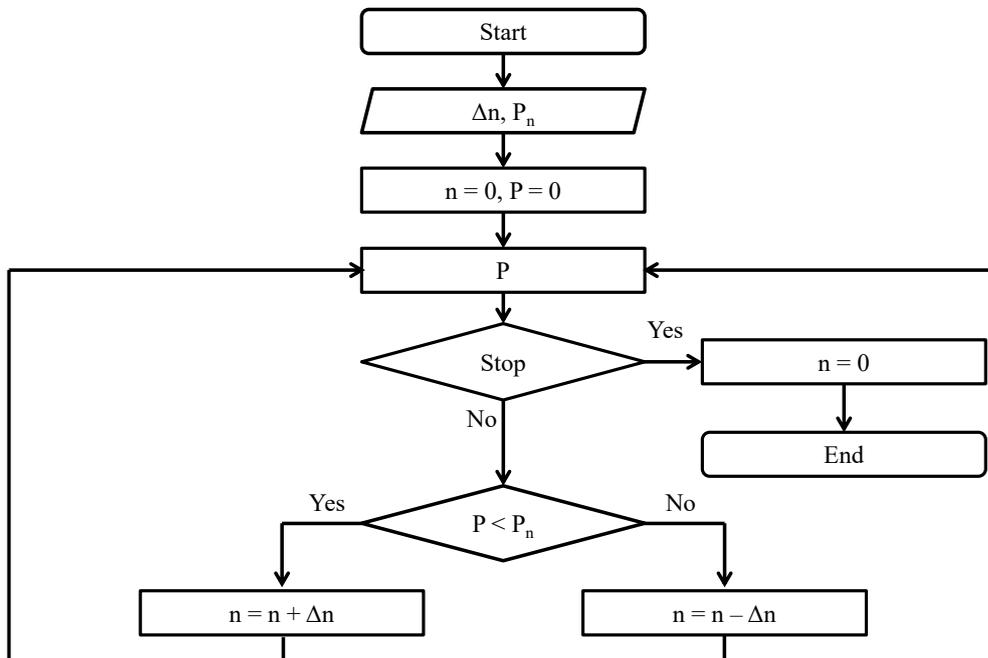


Fig. 7. Generally accepted algorithm for the servo control system of a rotary plate vacuum pump

6. If the condition $P < P_n$ is met – increase the rotational speed of the rotor of the vacuum pump n by step Δn , otherwise – decrease it.

7. Repeat the cycle from point 3.

Based on the results of research on the regime and technological parameters of the designed rotary plate vacuum pump HB-1200, a new algorithm for its servo control system was developed (Fig. 8), which includes the following:

1. Set the values of the given vacuum pressure in the vacuum system P_n and the step of variation of the rotor speed of the vacuum pump Δn , which depends on the air flow rate in the system Q_a according to (3).

2. Zero the initial values of vacuum pressure in the vacuum system $P=0$, the rotational speed of the rotor of the vacuum pump $n=0$, and the air flow rate in the system $Q_a=0$.

3. Measure the value of air flow rate in the system Q_a .

4. Calculate the variable speed step of the vacuum pump rotor $\Delta n (Q_a)$ using (2):

$$\Delta n = \frac{Q_a - 44.5436 + 1.56184P - 0.16936P^2 + 0.00266467P^3}{0.426725}. \quad (5)$$

5. Measure the vacuum pressure value in the vacuum system P .

6. In case of disconnection of the «Stop» button or emergency system – continue operations, otherwise – zero the rotor speed of the vacuum pump $n=0$; the end of the algorithm execution.

7. Compare the vacuum pressure value in the vacuum system P with the given P_n .

8. If the condition $P < P_n$ is met – increase the rotational speed of the rotor of the vacuum pump n by step $\Delta n (Q_a)$, otherwise – decrease it.

9. Repeat the cycle from point 3.

According to the devised methodology for the proposed algorithms, the dynamics of changes in vacuum pressure P and the rotational speed of the rotor of the vacuum pump n with a change in air flow rate Q_a of the milk-vacuum system of the milking machine were established (Fig. 9, 10).

Our analysis of Fig. 9 revealed that for the generally accepted algorithm, vacuum fluctuation increases with increasing air flow rate: at $\Delta Q_a=45$ l/min – $\Delta P=2.3$ kPa; at $\Delta Q_a=90$ l/min – $\Delta P=4.6$ kPa; at $\Delta Q_a=135$ l/min – $\Delta P=6.4$ kPa.

Unlike the generally accepted algorithm, the developed one provides a stable vacuum mode, which is confirmed by Fig. 10 – the largest vacuum fluctuation is $\Delta P=2.4$ kPa.

To check the energy efficiency of the proposed algorithms, plots of the change in the power of the vacuum pump drive on time t were constructed (Fig. 11).

It was established that the energy efficiency of the proposed algorithms is almost the same, as evidenced by the value of the area under the functions $N_p (t)$: for the generally accepted algorithm, $N_p \cdot t = 117.23$ kJ; for the developed algorithm, $N_p \cdot t = 127.19$ kJ.

Therefore, it can be argued that the developed algorithm provides a more stable vacuum regime of the milk-vacuum system $\Delta P=2.4$ kPa without reducing the energy efficiency.

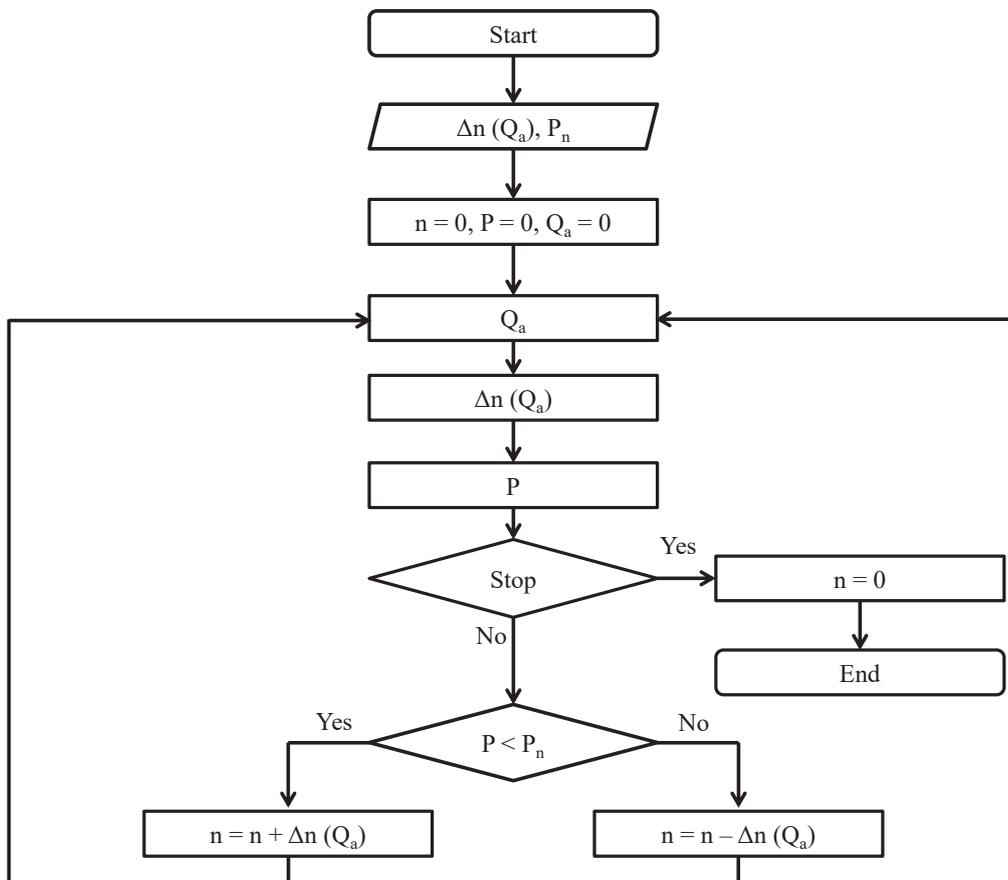


Fig. 8. Algorithm of the servo control system of a rotary plate vacuum pump

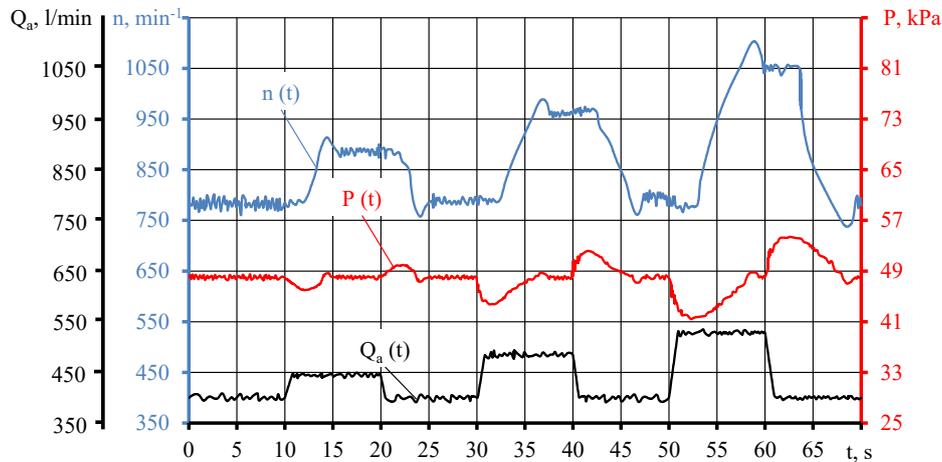


Fig. 9. Dynamics of changes in vacuum pressure P and rotor speed of vacuum pump n when changing air flow rate Q_a of a milk vacuum system of the milking machine for the generally accepted algorithm

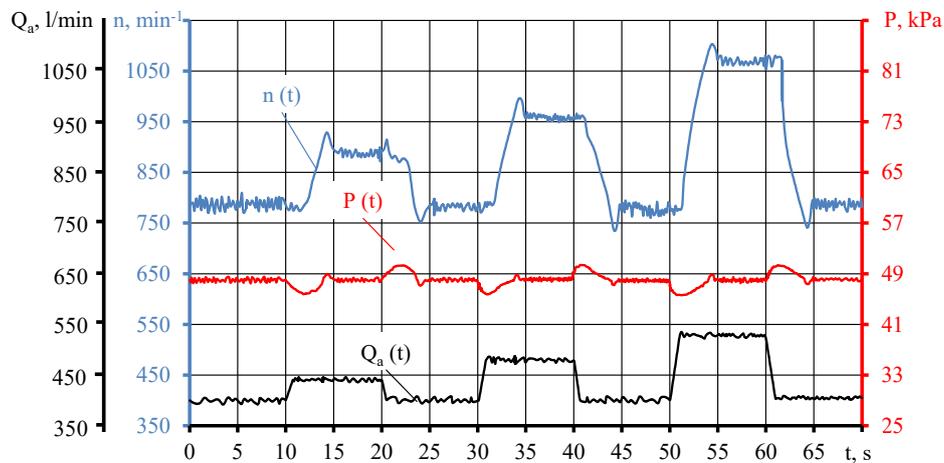


Fig. 10. Dynamics of changes in vacuum pressure P and rotor speed of vacuum pump n when changing air flow rate Q_a of a milk vacuum system of the milking machine for the developed algorithm

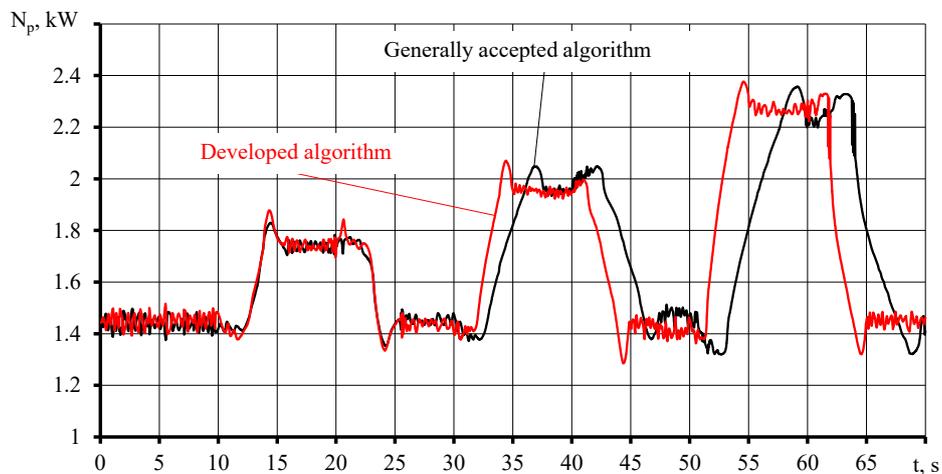


Fig. 11. Dynamics of changes in the power of the vacuum pump drive N_p for the proposed algorithms

6. Discussion of the feasibility of using an automated servo control system of the rotary plate vacuum pump

The structural and technological perfection of the vacuum pump affects the efficiency of all milking equipment and the energy intensity of the milking process [20].

In [21], it is noted that during milking, the equipment comes into close contact with cattle. Its technical parameters affect the effectiveness of the technological process of milking. The advantages of our research over that reported above are the justification of the parameters of the automatic servo control system of the rotary plate vacuum pump.

Thus, at the initial stage, the technological scheme of the servo control system of the rotary plate vacuum pump of the milking machine was built (Fig. 2). It was established that the use of the proposed system could reduce the energy consumption of the vacuum pump by $7.8 \pm 0.5\%$ of the milking machine and stabilize the vacuum pressure in the vacuum system to 2.4 kPa.

In the next stage, the influence of the regime parameters of the rotary plate vacuum pump on the efficiency of its operation was investigated. Based on the results of our research, a mathematical model of the influence of the studied factors on the performance of the vacuum pump was constructed.

Subsequently, according to the developed methodology for the proposed algorithms, the dynamics of changes in vacuum pressure P and rotor speed n were established. The dynamics were established when the air flow rate Q_a of the milk-vacuum system of the milking machine changes (Fig. 9, 10).

Our study was made possible owing to the use of innovative equipment (Fig. 1). This has made it possible to conduct a set of experiments to produce specific and reliable results.

The results of our research are consistent with the earlier studies reported in [22–24] while significantly complementing them. A significant difference in the methodological plan of the research was that it was possible to study the parameters of the automatic servo control system of the rotary plate vacuum pump of the milking machine.

Along with this, due to the extremely high variability of the design parameters of milking and dairy equipment, there are difficulties in fully resolving the issue of establishing the influence of the technical and technological parameters of the equipment on the efficiency of the machine milking process. This is still an unresolved issue in the overall technological link of milk production.

Under the conditions of application of the results, energy efficiency is improved and the vacuum stabilization process is enabled during the operation of milking machines. The results are a prerequisite and basis for the improvement and development of milking and dairy equipment. Studies aimed at developing a methodology for predicting the resource of the vacuum system of milking equipment are considered promising.

7. Conclusions

1. The technological scheme and principle of operation of the servo control system of rotary plate vacuum pumps have been developed. In accordance with them, to enable the same mode of control of vacuum pressure in a vacuum system, it is necessary that the changes in the air flow rate of the vacuum system relative to changes in vacuum pressure in it are the same. This applies to both increasing and decreasing the rotor speed of the vacuum pump.

2. We have established regularities in the influence of regime parameters (rotor speed n and vacuum pressure P) on the performance of the vacuum pump Q_a , vacuum pressure fluctuation ΔP , and the power consumption of the vacuum pump drive N_p . Based on these patterns, a new algorithm for the vacuum pump servo control system (on the example of HB-1200) was developed. It differs from the generally accepted one by the possibility of calculating the step of variation of the rotor speed depending on the performance of the vacuum pump Q_a and the value of the vacuum pressure P .

3. The servo control system of a rotary plate vacuum pump based on the developed algorithms of its operation was experimentally investigated. For the generally accepted algorithm, vacuum fluctuation increases with increasing an air flow rate: at $\Delta Q_a = 45$ l/min – $\Delta P = 2.3$ kPa; at $\Delta Q_a = 90$ l/min – $\Delta P = 4.6$ kPa; at $\Delta Q_a = 135$ l/min – $\Delta P = 6.4$ kPa. Unlike the generally accepted algorithm, the developed one provides a stable vacuum mode, the largest vacuum fluctuation is $\Delta P = 2.4$ kPa.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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