

IMPROVEMENT OF VACUUM PUMP DESIGN FOR MILKING ANIMALS

Vasyl Khmelovskiy, Victor Rebenko, Oleh Zabolotko, Viacheslav Bratishko

National University of Life and Environmental Sciences of Ukraine, Ukraine

hmelvas@ukr.net, rebenko@nubip.edu.ua, zabolotko@ukr.net, vbratishko@nubip.edu.ua

Abstract. The experience of manufacturers of milking equipment shows that the main sources of vacuum formation in milking installations are vacuum pumps of the rotary vane type. Compared to others, they have a high efficiency (0.8-0.9), low energy consumption (0.06-0.08 kWh·m⁻³), simplicity of construction and maintenance, and the possibility of direct connection with an electric motor. Despite the high performance, rotary vane type pumps have the possibility of improving their operational parameters. The task of our research is to theoretically substantiate the position of the inlet and outlet windows, as well as to study the design of the vacuum pump housing, which will allow increasing the air filling of the space between the vanes and ensuring the removal of air through the outlet window with minimal resistance. Research has shown that when the rotor rotates, forces act on the blades, which, depending on the angle of rotation of the rotor, have different magnitudes. Based on this, the application of the laws of mechanics made it possible to justify the position of the inlet and outlet windows. In the process of creating a vacuum, air enters through the inlet pipe to the intake window and does not fill the space between the two blades as much as possible, and when transporting the volume of air located between the two blades to the area of the exhaust window, a quick exit of air is not ensured, which leads to a slow decrease of the rotor turning resistance. This is due to the fact that the width of the inlet and outlet windows is 1/5 of the width of the vacuum pump body. The task is achieved by the fact that the intake window ends with a groove, the dimensions of which in the transverse direction are 4/5 of the width of the vacuum pump body and in the longitudinal direction at least 1/2 of the width of the intake window, and the outlet window, which has a transverse groove, the dimensions of which are similar to the dimensions of the inlet groove.

Keywords: vacuum, pump, transverse groove, inlet window, outlet window, air transportation, efficiency.

Introduction

Milking of farm animals is one of the most time-consuming and responsible processes in the technology of production of livestock products, namely milk. The effectiveness of the milking process is largely determined by compliance with the current rules of machine milking and the technical excellence of the used mechanization tools [1; 2]. The experience of manufacturers of equipment for milking animals shows that the main sources of vacuum formation in milking installations are vacuum pumps of the rotary vane type. It is the pump that has a significant impact on the productivity and energy consumption of the milking plant. The disadvantage of the rotary vane vacuum pump is that in the process of creating a vacuum, air moves through the inlet pipe to the inlet window and does not fill the space between the two vanes as much as possible. By moving the volume of air between the two blades to the exhaust window, the rapid release of air is not ensured and the resistance to rotation of the rotor in the area of the exhaust window is slowly reduced. This is due to the fact that the width of the inlet and outlet windows is 1/5 of the width of the vacuum pump body, and leads to an increase in energy indicators and a decrease in pump performance. These shortcomings can be corrected by increasing the volume of the inlet and outlet windows of the vacuum pump housing.

In works [3-5], the authors modelled physical processes in milking plants. However, these works do not fully illuminate the causes of vacuum fluctuations in milking installations and, accordingly, the ways to solve them.

The design and technological excellence of the vacuum pump has an impact on the energy consumption of the milking process and the restoration of vacuum pressure parameters in the milk-vacuum pipelines. During the milking process, the vacuum pump with constant productivity takes air from the vacuum and milk lines. Excess vacuum pressure is supplied to the atmosphere by the vacuum regulator. This approach to the operation of milking equipment leads to an increase in labour, energy and economic costs.

The increase in the productivity of the rotary vane vacuum pump in [6-8] occurred by increasing the number of vanes. The results of the experimental data showed that with an increase in the number of blades, the volumetric efficiency decreases. This is due to a decrease in the filling factor of the cells between the plates.

The researchers of the work [9-12] determined the performance of a vacuum pump with an initial engine rotation frequency of 800 revolutions per minute, with an interval of 100 revolutions up to the maximum allowed number of engine revolutions, i.e. 2820 revolutions per minute, frequency regulation was carried out using a converter frequency. Measurements showed that during milking, the average rotation frequency of the rotor, adjusted by the frequency converter, was 807 revolutions per minute, which corresponds to an air consumption of 770 litres per minute.

This means that during milking without a frequency converter, but using a valve regulator, the average value of additionally sucked air is 1280 litres per minute.

Materials and methods

The purpose of the research is to improve the vacuum pump housing, which will ensure an increase in air filling of the space between the vanes and the removal of air through the exhaust window with minimal resistance.

The task of improving the filling of the space between the blades and ensuring the rapid exit of air in the area of the outlet window is achieved by the fact that the inlet window ends (in the direction of rotor movement) with a groove, the dimensions of which in the transverse direction are 4/5 of the width of the vacuum pump housing and in the longitudinal direction at least 1/2 from the width of the inlet window, and the outlet window, which (in the direction of movement of the rotor) has a transverse groove, the dimensions of which are similar to the dimensions of the inlet groove.

The research was carried out using an experimental installation, which includes a vacuum pump of the rotor-blade type. The performance of the pump was measured using the KI-4840 device, the frequency of rotation of the rotor with an electronic (duplicated mechanical) tachometer, Fig. 1. The frequency of rotation of the rotor was changed using the frequency converter IEK Control-A310, this device also has the ability to record the magnitude of the current, voltage and frequency of the power grid, which are supplied to the electric motor. The temperature of the vacuum pump housing was measured with a pyrometer.

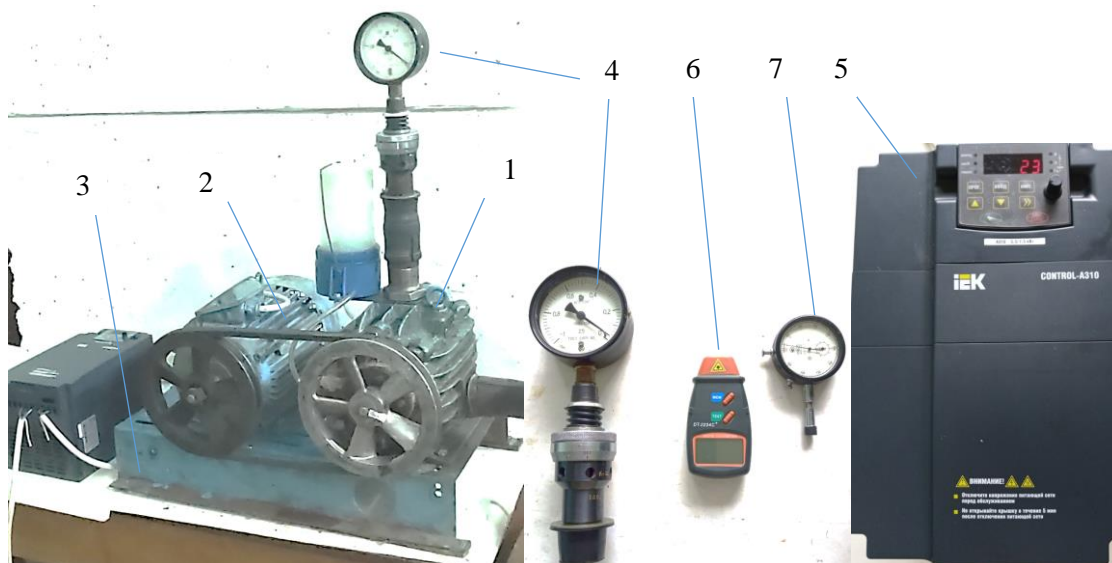


Fig. 1. **Experimental setup and devices:** 1 – rotary vane vacuum pump; 2 – electric motor; 3 – frame; 4 – flow meter KY-4840; 5 – frequency converter IEK Control-A310; 6 – electronic tachometer; 7 – mechanical tachometer

Results and discussion

Our studies have confirmed that the correct location of the inlet and outlet nozzles relative to the working surface contributes to the entry of air into the chamber and its removal from it, as well as shortens the length of the air compression zone and reduces its resistance at the exit from the pump. Based on this, it is necessary to justify the position of the windows, which depends on the correct definition of the dynamics of changes in the volume of the working chamber and the pressure in it

relative to the angle of rotation of the rotor, as well as the laws of mechanics. The results of the graphical modeling shown in Fig. 2 indicate that the connection between the blade space and the pressure window (discharge zone III) should occur at an angle value close to 90° , and the filling of the interblade space I occurs within 100° , zone II of air transportation and compression will be 120° , and idling IV - 50° .

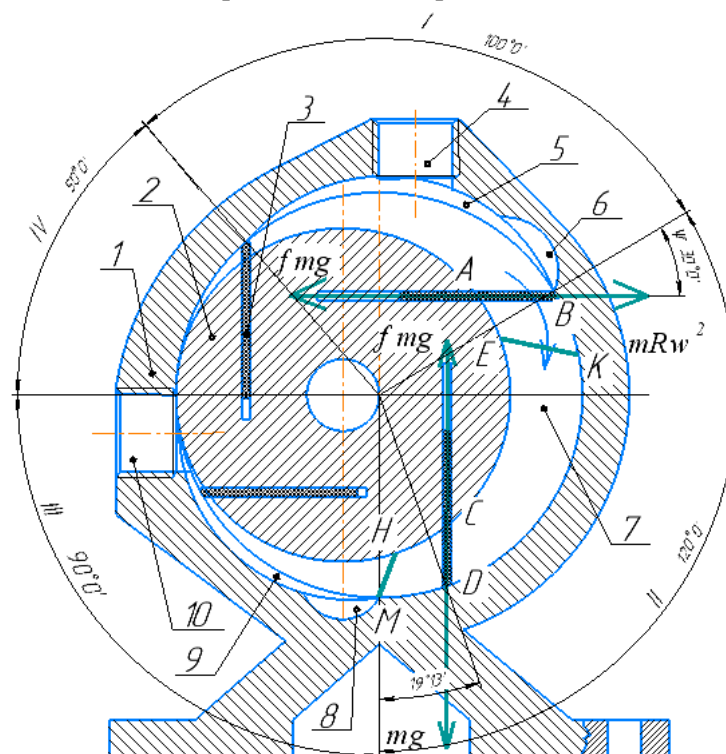


Fig. 2. **Structure of the vacuum pump and power analysis:** 1 – body; 2 – rotor; 3 – plates; 4 – inlet nozzle; 5 – inlet window; 6 – transverse groove of the inlet window; 7 – space between the blades; 8 – transverse groove of the outlet window; 9 – outlet window; 10 – outlet nozzle; mg – force of gravity; $mR\omega^2$ – centrifugal force of inertia; fmg – force of friction of the blade in the groove; α – angle of installation of the blade relative to the vertical axis

To create vacuum pressure in the pipelines of the milking plant, the rotor of the vacuum pump is set in motion, and with the help of inertial force, the blades come out of the grooves of the rotor and are pressed against the inner wall of the housing and create an isolated space between the two plates. Each vane that passes the suction window takes part of the air. The pressing of the plate occurs with the help of centrifugal force, however, the force of gravity and friction also act on the plate. Therefore, when the vane enters the unloading zone (the vane position is vertical), the distance between the rotor and the pump body gradually decreases, while the inertial force will approach the minimum value, while the force of the earth gravity is directed vertically downwards, and will approach the natural value when $\cos\alpha = 1$. Centrifugal force approaches the maximum value after the blade passes through the transverse groove of the intake window, which is designed to fill the space between the blades as much as possible. During further rotation of the rotor, the plate enters the transport zone II and performs the function of air movement in the space between the blades. Moving and compressing air requires more pressing of the plate against the pump body. The force analysis confirms the correctness of the selection of the transportation and compression zone because the plate is acted upon by forces that ensure an increase in the pressure of the plate against the body, as the pressure in the inter-blade space increases. In this zone, the distance between the rotor and the pump housing increases and reaches two values of eccentricity, as a result of which the inertia force will be maximum. During the operation of the pump, in the transportation zone, air is compressed and moved to the discharge zone. To quickly reduce the pressure, in the space between the blades, a transverse groove is installed at the beginning of the exhaust window, through which air moves to the exhaust window. The end of the exhaust window is provided in the place where the rotor and the housing have a minimum gap, and the inertia force of the blades is a minimum value. Such a solution is based on minimizing the harmful phenomenon that is present in

the vacuum pump, air entrapment at the end of the discharge zone. The idling zone should be minimal, but sufficient, to ensure the exit of the blade from the groove of the rotor and the acquisition of the minimum centrifugal force for taking air from the vacuum line of the milking unit.

As a result of increasing the length of the intake and exhaust windows, along the axis, and the placement of transverse grooves at the end of the intake (Fig. 3) and the beginning of the exhaust windows, it will be possible to increase the time and coefficient of filling the chamber with air. All these solutions will contribute to increasing the productivity, longevity of the vacuum pump and reducing energy consumption during its operation.

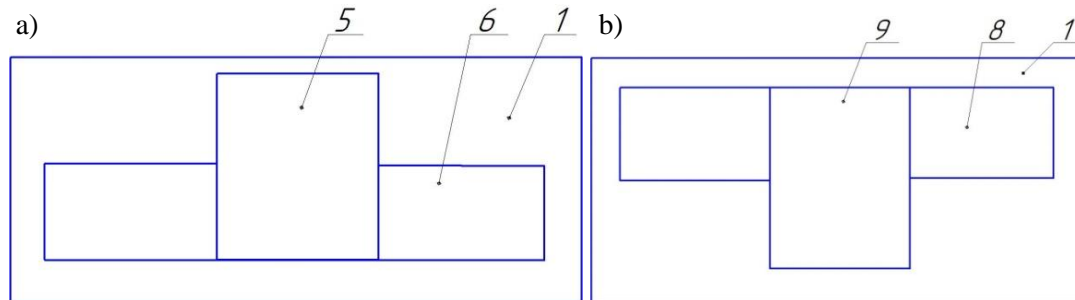


Fig. 3. Shape of the inlet (a) and exhaust (b) window

The efficiency of the milking plant will depend on the speed of transmission and processing of the signal from the vacuum pressure sensor and the electric motor drive system. Based on the level of vacuum pressure, the rotation frequency of the vacuum pump rotor can increase or decrease. Experimental data show that an increase in the frequency of rotation of the rotor provides a quick equalization of the vacuum pressure in the range of 50-53 kPa. With a significant decrease in the frequency of rotation of the rotor, the vacuum pump loses the ability to create vacuum pressure. This phenomenon is explained by the difference between the forces that ensure the movement of air in the vacuum pump and the forces that create the pressure of the blades against the pump stator (Fig. 2). When using a vacuum pump servo drive, there is a need to determine the minimum permissible rotation frequency of the pump rotor.

In the process of experimental research, using a laboratory setup, it was proven that the minimum allowable frequency of rotation of the rotor is 310 min^{-1} , however, this frequency does not allow stable creation of a vacuum, since there is an active flow of air between the plates. Stable creation of vacuum pressure in the range of 10-13 kPa occurs at a rotor rotation frequency of $380\text{-}400 \text{ min}^{-1}$. Fig. 4 shows the obtained dependences of rotation frequencies of the vacuum pump rotor and the power consumption of the basic and advanced options, depending on the performance of the vacuum pump. In the course of the experiment, the frequency of rotation of the vacuum pump rotor was determined using electronic and mechanical tachometers, the pump performance using a KI-4840 flow meter, and the power consumption for pump motion by multiplying the current and voltage obtained from the IEK Control-A310 frequency converter. All experiments were performed at a vacuum pressure of 50 kPa. During each experiment, the temperature of the vacuum pump body was checked with a pyrometer at three points: near the pulley, in the centre of the pump, and on the closed lid.

The theoretical prerequisites prove that the pressure in the working chamber, between the plates of the vacuum pump, can be determined by the expression [1; 2].

$$P = P_{st} \cdot \left(\frac{S_{st}}{S_{k\varphi}} \right)^\gamma, \text{ kPa} \quad (1)$$

where P_{st} – gas pressure at the beginning of compression (equal to the suction pressure), kPa ;
 S_{st} – initial cross-sectional area of the EKHM working chamber, m^2 ;
 $S_{k\varphi}$ – cross-sectional area of the EKHM working chamber at the rotation angle φ , m^2 ;
 γ – polytropy index.

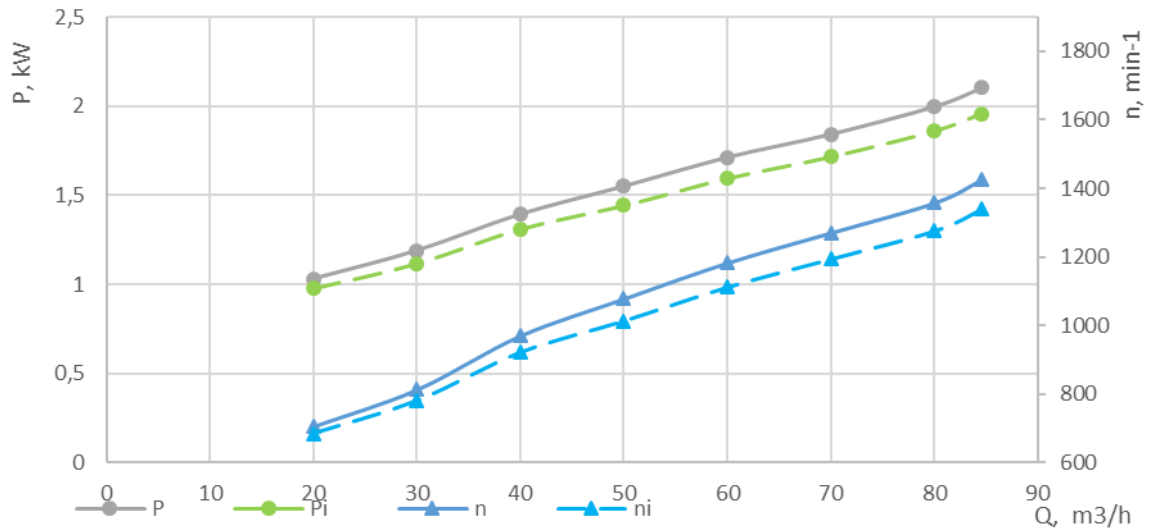


Fig. 4. Experimental studies of dependence of rotor rotation frequencies (n and n_i), min^{-1} and power consumption (P and P_i), kW of the basic and improved options on the performance (Q), $\text{m}^3\cdot\text{h}^{-1}$ of the vacuum pump

By substituting the value of P_{st} into expression (1) = 30 kPa and taking into account the previous considerations, we will get the pressure value in the working chamber. The resulting dependence does not fully reflect the actual pressure change in the working chamber, since it does not take into account internal flows in the pump and thermodynamic air variables. However, to determine the forces acting on the plate to prevent air flow between the plates, this relationship is quite suitable.

The pressing force of the vane depends on the geometric dimensions of the vacuum pump and the frequency of rotation of the rotor. The amount of pressure that is in the chamber, in front of the outlet window, creates conditions for the flow of air in the middle of the vacuum pump. To prevent such a phenomenon, it is necessary to provide a condition

$$Plb \leq mR\omega^2 - fmg + mg \cos \alpha, \text{ N} \quad (2)$$

where P – vacuum pressure, Pa;
 l – plate length, m;
 b – plate thickness, m;
 m – plate weight, kg;
 R – radius of the plate exit from the rotor groove, m;
 ω – angular speed of rotation of the rotor, s^{-1} ;
 f – coefficient of friction of the plate on the surface of the rotor groove;
 g – acceleration of gravity, $\text{m}\cdot\text{s}^{-2}$;
 α – blade installation angle relative to the vertical axis.

Given the equality of expression (2), we determine the force acting on the blade (the left part of the expression) and the direction to the axis of rotation of the rotor (repulsion of the blade). In this part, we change the vacuum pressure, we get the theoretical dependence. In the right part of equation (2), we determine the force of pressing the vane against the vacuum pump housing. In the right-hand side of the expression, all components have a constant value except for ω . To ensure the equality of expression (2) when the vacuum pressure changes in the left part of the expression, it is necessary to change the angular speed of rotation of the rotor. The results of the theoretical justification of the frequency of rotation of the rotor are shown in the graph of Fig. 5.

During the experiments, the temperature of the vacuum pump housing was measured at three points: near the pulley, in the centre of the housing near the entrance window, and near the bearing cover. The temperature range was 67-85 °C. When conducting similar studies with an improved pump housing, its heating was within 60-73 °C.

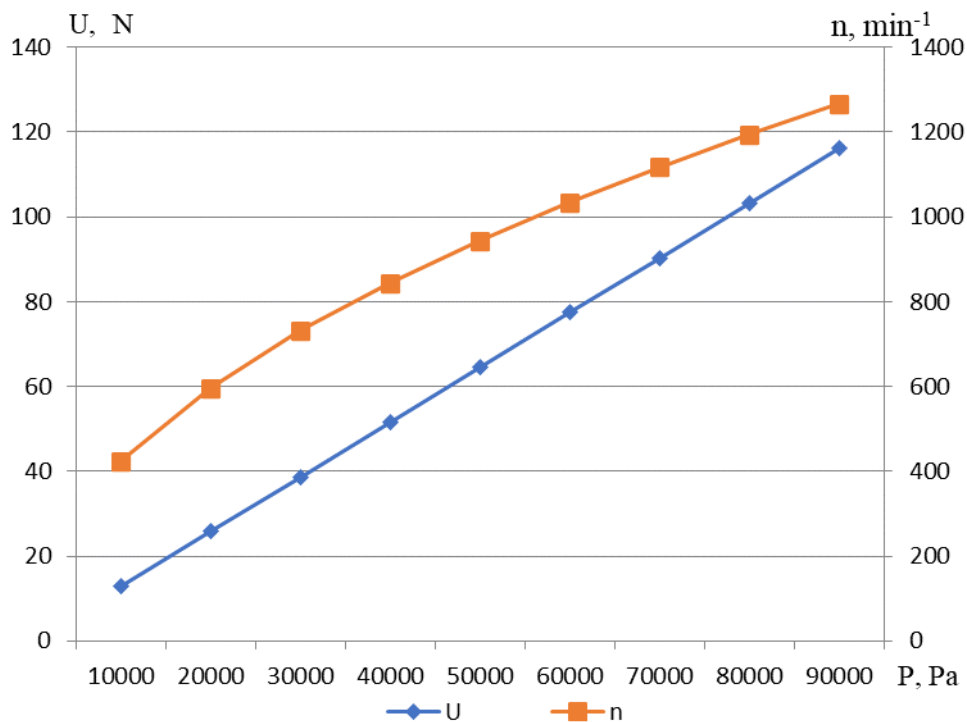


Fig. 4. Dependencies of the rotor rotation frequency (n) min^{-1} and blade repulsion force (U), N on the vacuum pressure (P), Pa of the vacuum pump

Conclusions

1. From the above, it is clear that the justified choice of the position and size of the windows primarily depends on the correct definition of the dynamics of changes in the volume of the working chamber and the pressure in it, relative to the angle of rotation of the rotor, as well as the laws of mechanics. Improving the filling of the space between the blades and ensuring rapid exit of air in the area of the outlet window is achieved by the fact that the inlet window ends (in the direction of movement of the rotor) with a groove, the dimensions of which in the transverse direction are $4/5$ of the width of the vacuum pump housing and in the longitudinal direction at least $1/2$ of the width of the intake window, and the outlet window, which at the beginning has a transverse groove, the dimensions of which are similar to the dimensions of the intake groove.
2. It has been proven that the minimum permissible frequency of rotation of the rotor is 310 min^{-1} , however, this frequency does not provide an opportunity to create a stable vacuum, since there is an active flow of air between the plates. Stable creation of vacuum pressure in the range of $10\text{-}13 \text{ kPa}$ occurs at a rotor rotation frequency of $380\text{-}400 \text{ min}^{-1}$.
3. The improved design of the vacuum pump casing makes it possible to increase the performance of the pump by $7\text{-}12\%$ and reduce the power consumption for its movement by $6\text{-}10\%$, in addition, there is a decrease in the heating of the casing to $60\text{-}73 \text{ }^\circ\text{C}$.

Author contributions

Conceptualization, methodology, project administration, V.K. and V.B.; data curation, visualization, V.R. and O.Z.; writing and editing, V.K. and V.R. All authors have read and agreed to the published version of the manuscript.

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