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ANALYTICAL STUDIES OF THE STRUCTURAL AND OPERATING PARAMETERS OF THE COLLECTOR OF AN ADAPTIVE MILKING MACHINE

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The paper addresses the problem of improving the efficiency of machine milking by enhancing the design of the milking machine collector with due consideration of the physiological characteristics of animals. It is shown that most commercial collectors operate under fixed regimes and do not provide individual adaptation of vacuum parameters to variations in milk flow intensity, which may result in incomplete milk extraction, longer milking time, and negative effects on udder health.

The purpose of the study is to develop the design of an adaptive milking machine collector and to analytically substantiate its structural and operating parameters that ensure stable transportation of the milk–air mixture and optimal milking conditions. The object of the research is the operation process of the collector as part of a two-stroke milking machine, while the subject of the research is the relationships between its geometric parameters and operating modes.

An adaptive collector design with additional air chambers, a membrane–valve mechanism, and an adjustable throttle channel is proposed. Using analytical, computational-graphical, and physical–mathematical methods, the relationships between the throttle orifice diameter and air flow rate, the diameter of the milk hose outlet and the parameters of the milk–air mixture, as well as between the operating parameters of the milking machine and the volume of the collector milk chamber, were established.

Rational values of the design parameters were substantiated: throttle channel diameter of 1.1–2.7 mm, milk hose outlet diameter of 8–16 mm, and milk chamber volume of 121 cm³. Pulsograms of the milking machine operation with the developed collector were constructed, and the durations of the operating strokes and vacuum pressure levels were determined. The obtained results confirm the feasibility of using an adaptive milking collector to increase milking speed, stabilize the vacuum regime, and improve the operating conditions of milking installations.

Keywords: *milking machine, adaptive collector, vacuum regime, milk–air mixture, pulsation, machine milking*

Eq. 27. Fig. 4. Ref. 15.

1. Problem formulation

Modern machine milking systems are required to ensure high productivity while strictly complying with the physiological requirements of dairy animals. One of the key functional elements of a milking machine is the collector, which provides milk accumulation, stabilization of vacuum pressure, and transportation of the milk–air mixture from the teat cups to the milk line. However, most collectors used in conventional milking machines operate under fixed regime parameters and do not take into account the individual characteristics of animals, such as differences in milk flow intensity, teat canal resistance, or sensitivity to vacuum fluctuations [1–2].

Scientific studies and practical experience indicate that non-adaptive milking regimes can lead to incomplete milk extraction, increased milking time, and negative impact on the functional state of the udder, which in turn raises the risk of mastitis and reduces the productive longevity of cows. According to FAO and IDF recommendations, maintaining stable vacuum levels and optimal pulsation characteristics is a critical condition for animal welfare and milk quality [2–3].

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Existing designs of milking machine collectors are mainly focused on mechanical simplicity and manufacturability, while issues of adaptive regulation of vacuum pressure and milk flow remain insufficiently addressed. Research presented in open scientific sources shows that changes in the geometry of air and milk channels, as well as in the volume of the milk chamber, significantly affect pressure gradients and the dynamics of milk–air mixture transport [4–5]

Therefore, there is a scientific and practical problem of developing an adaptive milking collector capable of automatically adjusting its operating parameters during the milking process. Such a collector should ensure stable transportation of milk, minimize vacuum fluctuations in the teat chamber, and meet physiological requirements under varying operating conditions. Solving this problem requires analytical substantiation of the relationships between the constructive parameters of the collector and its operating modes, which forms the basis of the present study.

2. Analysis of recent research and publications

Recent scientific publications on milking machine technology show a clear research interest in improving collector designs and vacuum systemsto enhance milking efficiency and animal welfare. A study by [6] establishes that the structural and technological parameters of a milking machine collector significantly affect the efficiency of milk transportation and the completeness of milking. It highlights that traditional collector designs often perform inefficiently and that adjusting parameters such as the volume of the milk chamber and throttle opening can improve performance by optimizing pressure gradients during milk flow.

Similar research from Ukrainian agricultural universities also focuses on technical and technological parameters of milking equipment, constructing mathematical models that relate vacuum levels, pulsation frequency, and other operational variables to the rate of milk yield, thereby providing theoretical foundations for optimizing machine milking performance [7]. Additionally, work on interconnections between technical parameters and the dynamics of milk–air mixture movement demonstrates the importance of understanding fluid dynamics within the milking system as a basis for improving equipment design and operation [8].

Other international research explores vacuum control and stability, such as the use of flow-controlled vacuum regulation systems in milking machines. These systems adapt vacuum levels according to actual flow rate, reducing fluctuations and potentially improving milking efficiency and teat condition, which aligns with the physiological considerations addressed by adaptive collector design [9–10].

Historical engineering studies presented at conferences also propose adaptive and autonomous control systems for milking apparatuses that adjust the milk flow and vacuum based on real-time operating conditions to enhance overall performance [11–12].

Collectively, this body of research supports the need for adaptive milking machine components – including collectors – that can dynamically respond to changing conditions during milking to improve both machine performance and animal well-being.

3. The purpose of the article

The purpose of the study is to develop the design of an adaptive milking machine collector and to analytically substantiate its structural and operating parameters that ensure individual adaptation of milking modes to the physiological characteristics of animals during the milking process, by determining rational geometric parameters of air and milk channels, the volume of the milk chamber, and vacuum operating modes required for stable transportation of the milk–air mixture and efficient operation of the milking machine.

4. Results and discussion

From the analysis of existing types of milking machine collectors, we conclude that it is necessary to develop an adaptive milking collector that would have a simple design and ensure high milking speed. The development of the adaptive milking collector will be carried out based on the two-chamber collector ADU.03.000 by adding two additional air chambers.

The main components and parts of the adaptive milking collector (Fig. 1) are: a plastic body 1, which functions as the milk collection chamber K1 with a drain pipe; chamber 2 with connectors for the milking cups; cup 3, which is a continuation of chamber 2; variable vacuum chamber 4, divided by cup 5 into upper 6 (K3) and lower 7 (K2) parts; membrane 8, which limits the lower part of the variable vacuum chamber 7 from below and is secured with nuts 12; one-way valve 9; valve 10 equipped with a limiter 11, which also serves as a seal; adjustable screw 13; vacuum distributor 14 (K4) installed on the variable vacuum chamber 4; and valve 15.

The adaptive milking collector, as part of a two-stroke milking machine, operates as follows (figs. 2–3). During milking, valve 15 is open. During the suction stroke, milk from the milking cups enters the plastic body 1 (K1) through the connectors. As milk flow increases, the vacuum in body 1 (K1) decreases, the membrane 8 deflects upward, opens valve 10, and atmospheric air flows from the lower part of the variable vacuum chamber (K2) into the upper part (K3), then through the hole with adjustable screw 13, through the one-way valve 9, into body 1 (K1), which contributes to accelerating milk evacuation into the milk pipeline.

During the compression stroke, the original vacuum level in body 1 (K1) is restored by the membrane 8 deflecting downward and closing valve 10. At the end of milking, valve 15 is closed manually, thereby disconnecting the vacuum from the collector.

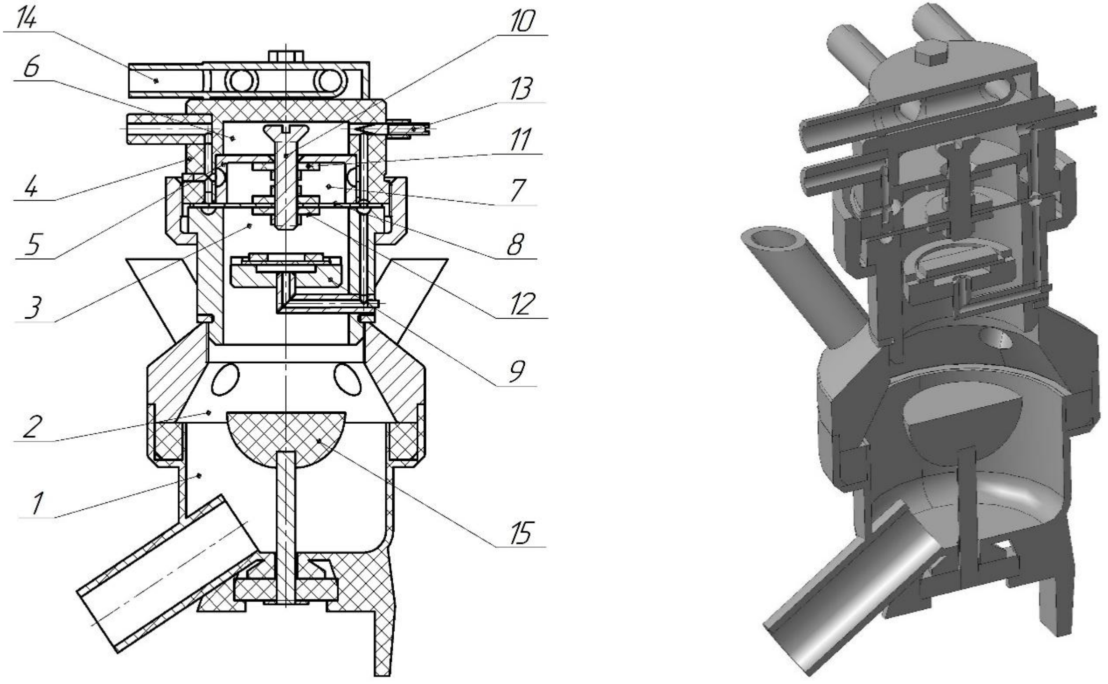

Fig. 1. Design scheme of the adaptive milking collector:
1 – plastic body (K1); 2 – chamber; 3 – cup; 4 – variable vacuum chamber; 5 – cup; 6 – upper part of the cup (K3); 7 – lower part (K2); 8 – membrane; 9 – one-way valve; 10 – valve; 11 – limiter; 12 – nut; 13 – adjustable screw; 14 – vacuum distributor (K4); 15 – valve

The operating mode of the adaptive milking collector as part of a two-stroke milking machine is determined by the time intervals during which the valve switches (Figs. 2–3). The calculation is based on taking into account the patterns observed when air flows from one chamber to another through the throttle channel and the milk-filled collection chamber.

The suction stroke t_{cc} of the two-stroke milking machine with the developed collector can be divided into three stages (Figs. 2–3): t_1 – filling the collector’s milk chamber with milk; t_2 – air flow through the one-way valve and throttle channel into the milk chamber; t_3 – emptying the collector’s milk chamber of milk.

A combined analytical and computational-graphical approach was applied to study the operation of the developed adaptive milking collector, which included the following stages:

– Analysis of throttle channel and milk hose parameters. The relationship between the diameter of the throttle orifice and air flow rate was determined to identify the optimal channel diameter for generating the required pressure gradient for milk transport. Similarly, the relationship between the density of the milk–air mixture, milking intensity, and the diameter of the milk hose outlet was established to determine the optimal dimensions for efficient milk transportation under various pressure gradients.

– Determination of the collector milk chamber volume. Using Boyle’s law and force equilibrium equations for the valve and membrane, the milk chamber volume was calculated. The process of filling the chamber during the suction stroke, changes in vacuum pressure, and air flow through the one-way valve and throttle channel were taken into account. These calculations allow determination of the filling and emptying times of the milk chamber, ensuring synchronization with the two-stroke pulsator cycle.

– Construction of the milking machine pulsogram. The working cycle of the milking machine was graphically modeled as indicator pulsograms showing the vacuum pressure variation in the inter-wall and teatcup chambers. Based on the calculated time intervals, the durations of suction and compression strokes were determined, and the ideal pulsogram of the developed collector operation was constructed.

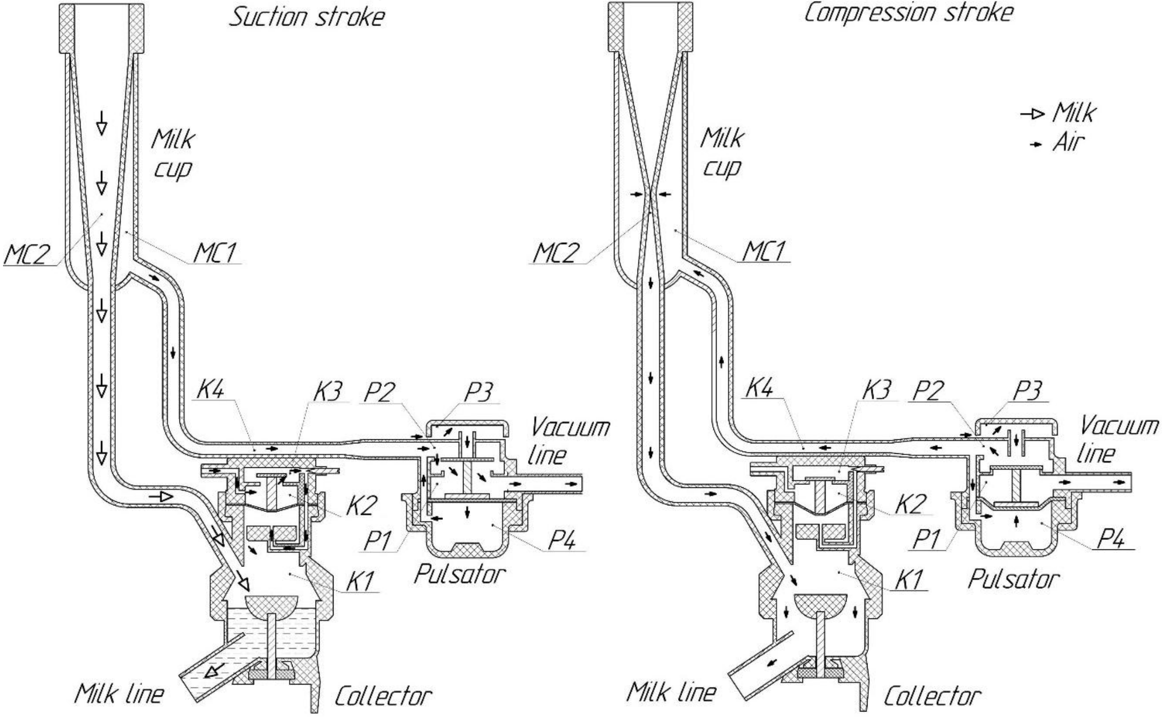

Fig. 2. Diagram of the operating principle of a milking machine with an adaptive milking collector

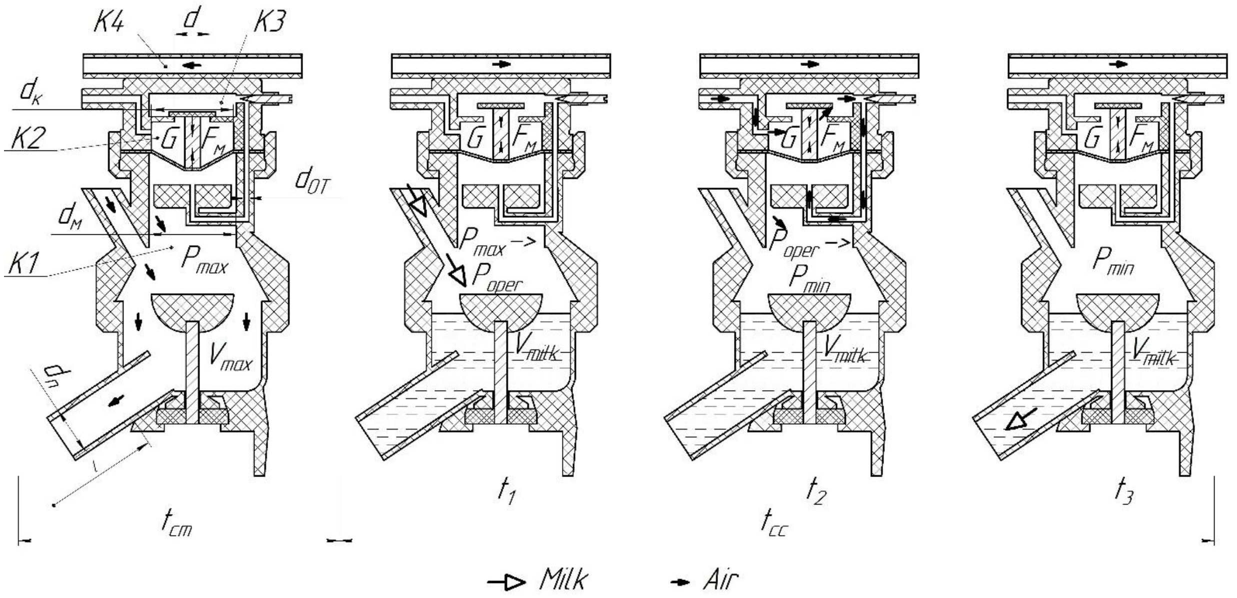

Fig. 3. Calculation scheme of the adaptive milking collector operation

Calculation of milking speed and milking unit operation time. Milking speed was calculated based on the milk chamber volume and operating vacuum pressure. Using the obtained milking speed and technical parameters of the milking unit, the duration of a single milking session and the total operating time of the unit were determined for both the standard and developed collector variants.

The relationship between the diameter of the throttle orifice and the air flow rate is described by the following equation [13–14]:

$$d_{\text{ОТ}}^4 = (\lambda + \varepsilon)\cdot 0{,}811\frac{q_{\text{П}}^2}{gRT}, \qquad (1)$$

where $d_{\text{ОТ}}$ – diameter of the throttle orifice, m; λ, ε – coefficients of linear and local resistance of the air duct; q_P – air flow rate, m³/s; g – acceleration due to gravity, m/s²; R – specific gas constant for air, R = 29.27 m/K; T – air temperature, K.

Analysis of the obtained dependence (1) indicates that the optimal diameter of the throttle channel, sufficient to create the pressure gradient necessary for transporting a portion of milk, lies within the range of 1.1–2.7 mm.

The relationship between the density of the milk–air mixture, milking intensity, and the diameter of the milk hose outlet is described by the following equation [13–14]:

$$d_n^{\,5} = \frac{0{,}811\cdot\lambda\cdot l\cdot\rho_{cm}\cdot q_m^{\,2}}{\Delta P-\rho_{cm}\cdot g\cdot h}, \tag{2}$$

where d_n – diameter of the milk hose outlet, m; λ – resistance coefficient; l – length of the milk hose, m; ρ – density of the milk mixture, kg/m³; q_m – milk flow rate, m³/s; ΔP – pressure gradient, Pa; h – height to which milk needs to be transported, m.

Analysis of the obtained dependence (2) shows that the optimal diameter of the milk hose outlet, sufficient for transporting a milk–air mixture with a density of 200–600 kg/m³ under various pressure gradients, ranges from 8 to 16 mm.

During the suction stroke of a two-stroke milking machine, the milk chamber of the collector is filled with milk. At the same time, the vacuum pressure in the collector milk chamber, and consequently in the teat space of the milking cups, decreases. Assuming that milk is an incompressible liquid, according to Boyle–Mariotte's law, we obtain:

$$P_{oper}\left(V_{max}-V_{milk}\right)=V_{max}P_{max}, \tag{3}$$

where P_{oper} – minimum vacuum pressure in the milk chamber at which the valve opens, Pa; V_{max} – volume of the milk chamber, m^3; V_{milk} – volume of milk that has filled the milk chamber, m^3.

From equation (3), we obtain:

$$V_{milk}=V_{max}\left(\frac{P_{max}}{P_{oper}}-1\right). \tag{4}$$

The time required for milk to fill the volume V_{milk} of the collector milk chamber is determined by the equation:

$$t_1=\frac{Q_{max}}{V_{milk}}=\frac{Q_{max}}{V_{max}\left(\frac{P_{max}}{P_{oper}}-1\right)}, \tag{5}$$

where Q_{max} – milk flow rate from the animal's udder, m^3/s.

According to the force equilibrium equation acting on the valve and the membrane, we have:

$$P_{oper}uS_m=G-F_m \tag{6}$$

where S_m – membrane area, m^2:

$$S_m=\frac{1}{4}\pi d_к^2, \tag{7}$$

where G – gravitational force of the moving parts (valve and membrane), N; F_m – elastic force of the membrane, N; u – membrane activity coefficient [15],

$$u=\frac{\frac{1}{3}+\frac{d_k}{d_m}+\left(\frac{d_k}{d_m}\right)^2}{1+\frac{2d_k}{d_m}+\left(\frac{d_k}{d_m}\right)^2}; \tag{8}$$

where d_k – inner diameter of the membrane, m; d_m – outer diameter of the membrane, m.

From equation (6), we obtain:

$$P_{oper}=\frac{G-F_m}{uS_m}. \tag{9}$$

Finally, the time during which the vacuum pressure changes from P_{max} to P_{max} is:

$$t_1 = \frac{Q_{max}}{V_{max}\left(P_{max}\frac{u\pi d_{\text{к}}^2}{4\left(G - F_m\right)} - 1\right)}. \tag{10}$$

After the collector valve opens, during time t_2, air begins to flow through the one-way valve and the throttle channel into the milk chamber, changing the pressure from P_{oper} to P_{min}. The rate of change of vacuum pressure is determined by the following relationship:

$$\frac{dP(t)}{dt} = \frac{k_p}{V_{max}}P(t), \tag{11}$$

where P(t) – vacuum pressure at time t, Pa; k_p – poiseuille coefficient accounting for channel dimensions and air viscosity, $k_p = \pi d_{OT}^4 / \left(128 l_{OT}\eta_B\right)$; d_{OT}, l_{OT} – diameter and length of the channel connecting the pulsator chambers, m; $\eta_{\text{в}}$ – dynamic viscosity of air, Pa·s.

From equation (11), we obtain:

$$t_2 = \frac{V_{max}}{k_p}\int_{P_{oper}}^{P_{min}}\frac{dP}{P} = \frac{V_{max}}{k_p}\ln\frac{P_{oper}}{P_{min}} = \frac{128 l_{OT}\eta_B V_{max}}{\pi d_{OT}^4}\ln\frac{4\left(G - F_m\right)}{u\pi d_k^2 P_{min}}, \tag{12}$$

where P_{min} – minimum vacuum pressure at which the suspension unit remains attached to the teats, Pa.

During time t_3, due to the created concentration gradient $P_{max} - P_{min}$, milk is discharged from the collector milk chamber:

$$t_3 = \frac{Q}{V_{milk}}, \tag{13}$$

where Q – milk flow rate through the outlet nipple of the milk hose, m^3/s.

The Bernoulli equation is formulated for the process of milk flow through the outlet nipple of the milk hose:

$$\frac{P_{max}}{\rho g} = \frac{P_{min}}{\rho g} + \frac{\upsilon^2}{2g}, \tag{14}$$

where ρ – milk density, kg/m^3; g – acceleration due to gravity, m/s^2; υ – velocity of milk flow in the milk hose nipple, m/s.

The milk flow velocity is expressed through the nipple diameter d_p and milk flow rate Q_{max}. The average milk flow velocity is:

$$\upsilon = \frac{4Q_{max}}{\pi d_n^2}. \tag{15}$$

Substituting equation (14) into equation (15) and performing the corresponding transformations, we obtain:

$$Q_{max} = \pi d_{\text{п}}^2\sqrt{\frac{P_{max} - P_{min}}{8\rho}}. \tag{16}$$

Finally, we obtain:

$$t_3 = \frac{\pi d_n^2\sqrt{\frac{P_{max} - P_{min}}{8\rho}}}{V_{max}\left(P_{max}\frac{u\pi d_{\text{к}}^2}{4\left(G - F_m\right)} - 1\right)}. \tag{17}$$

The total response time of the collector valve $t_1 + t_2 + t_3$ must be equal to the duration of the suction stroke of the two-stroke pulsator t_{cc}:

$$\frac{Q_{max}}{V_{max}\left(P_{max}\frac{u\pi d_k^2}{4\left(G - F_m\right)} - 1\right)} + \frac{128 l_{OT}\eta_B V_{max}}{\pi d_{OT}^4}\ln\frac{4\left(G - F_m\right)}{u\pi d_{\text{к}}^2 P_{min}} + \frac{\pi d_{\text{п}}^2\sqrt{\frac{P_{max} - P_{min}}{8\rho}}}{V_{max}\left(P_{max}\frac{u\pi d_{\text{к}}^2}{4\left(G - F_m\right)} - 1\right)} = t_{cc}. \tag{18}$$

From equation (18), an expression for determining the volume of the collector milk chamber is obtained V_{max}:

$$V_{\max}=\frac{t_{cc}+\sqrt{A_4^2-4A_3\left(A_1+A_2\right)}}{2A_3}, \tag{19}$$

where

$$A_1=\frac{\dfrac{\pi d^2}{4}\sqrt{\dfrac{P_0-P_{\max}+\rho gL}{\rho}}}{\left(P_{\max}\dfrac{u\pi d_k^2}{4\left(G-F_m\right)}-1\right)}; \tag{20}$$

$$A_2=\frac{\dfrac{\pi d_п^2}{4}\sqrt{\dfrac{2\left(P_{\max}-P_{\min}\right)}{\rho}}}{\left(P_{\max}\dfrac{u\pi d_k^2}{4\left(G-F_m\right)}-1\right)}; \tag{21}$$

$$A_3=\frac{128 l_{OT}\eta_B}{\pi d_{OT}^4}\ln\frac{4\left(G-F_m\right)}{u\pi d_k^2 P_{\min}}. \tag{22}$$

Substituting the determined design parameters of the collector and the operating parameters of the two-stroke milking machine into equations (19)–(22), the volume of the milk chamber of the developed collector is obtained and equals 121 cm^3.

The calculation of the developed collector as part of the milking machine involves determining the duration of the operating strokes. The working cycle of the milking machine is graphically represented in the form of indicator pulsograms, which show the variation of vacuum pressure over time in the inter-wall and teat chambers of the milking cup.

For a two-stroke milking machine, a characteristic ratio of suction and compression strokes is used, which is determined by the expression:

$$\delta=\frac{t_{cc}}{t_{cm}}=\frac{60}{40}; \tag{23}$$

and the pulsation frequency, which is determined by the equation:

$$n=\frac{1}{t_{cc}+t_{cm}}=60\ \text{imp./min.} \tag{24}$$

From these expressions, the following values are obtained: t_{cc} = 0.6 s and t_{cm} = 0.4 s. The operating vacuum pressure in the vacuum system is 48 kPa.

By substituting the determined design parameters of the collector into equations (10), (12), and (17), the following time intervals are obtained: t_1 = 0.16 s, t_2 = 0.33 s, and t_3 = 0.11 s. For these intervals, the vacuum pressures take the following values: P_{oper} = 39 kPa (according to equation (9)) and $P_{\min}$ = 20 kPa.

Figure 3 presents the pulsogram of the ideal operating process of the developed collector as part of a two-stroke milking machine.

The milking speed is calculated using the following formula:

$$\vartheta=nV_{milk}=nV_{\max}\left(\frac{P_{\max}}{P_{oper}}-1\right)=60\cdot0.121\cdot(48/39-1)=1.67\ \text{L/min.} \tag{25}$$

Considering that the average milking speed of a standard ADU milking machine equipped with a serial two-chamber collector is 1.5 L/min, the duration of a single milking operation is calculated for a UDM-200 milking installation with 12 milking units:

$$t_0=\frac{H\cdot N}{60\cdot D\cdot m\cdot\vartheta\cdot N_{MU}},\ \text{h}, \tag{26}$$

where H – annual milk yield, l; N– number of animals; D – lactation period, days; m– milking frequency; N_{MU}– number of milking units.

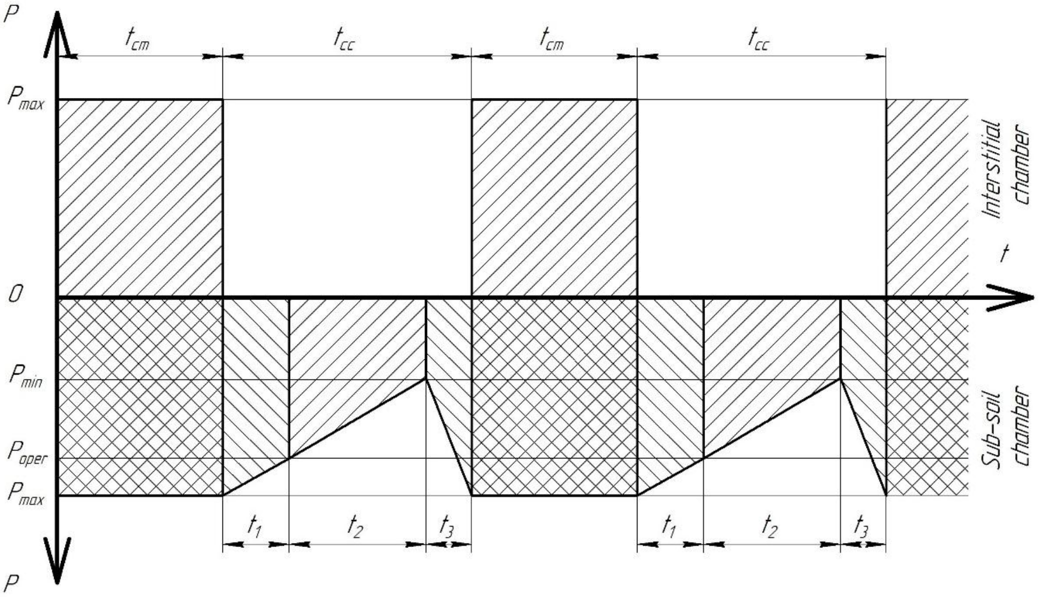

Fig. 4. Pulsogram of the ideal operating process of the developed collector as part of a two-stroke milking machine

According to the calculations in Section 2, the following results are obtained:

for the base variant: $t_0 = \dfrac{4500 \cdot 200}{60 \cdot 300 \cdot 2 \cdot 1.5 \cdot 12} = 1.39$ h;

for the developed variant: $t_0 = \dfrac{4500 \cdot 200}{60 \cdot 300 \cdot 2 \cdot 1.67 \cdot 12} = 1.25$ h.

The operating time of the milking installation is determined by the equation:

$$t_Д = t_0 \cdot D \cdot m, \text{ h.} \qquad (27)$$

Finally, the following values are obtained:

for the base variant: $t_D = 1.39 \cdot 300 \cdot 2 = 833$ h;

for the developed variant: $t_D = 1{,}25 \cdot 300 \cdot 2 = 749$ h.

5. Conclusion

As a result of the analysis of existing types of milking machine collectors, the design of an adaptive milking collector was developed. The proposed collector meets physiological requirements by adapting its operating modes individually to each animal directly during the milking process. The developed adaptive milking collector consists of a plastic body (K1), chamber, cup, variable vacuum chamber, cup, upper part of the cup (K3), lower part (K2), membrane, one-way valve, valve, limiter, nut, adjustable screw, vacuum distributor (K4), and valve.

The design parameters of the developed adaptive milking collector were substantiated. The dependence of the air duct diameter d_{OT} on the air flow rate and the reduced resistance coefficient was determined. The dependence of the milk hose outlet diameter d_n on the density and flow rate of the milk–air mixture under a given pressure gradient was established. The rational diameter of the throttle channel, sufficient to create the pressure gradient required for transporting a portion of milk, was found to be within the range of 1.1–2.7 mm. The rational diameter of the milk hose outlet, sufficient for transporting a milk–air mixture with a density of 200–600 kg/m³ under various pressure gradients, lies within the range of 8–16 mm.

The relationships between the operating parameters of the adaptive milking collector (pulsation frequency and stroke ratio) and the volume of its milk chamber were established. Taking into account the adopted technological parameters of the machine milking process, the rational volume of the milk chamber of the developed collector was determined to be 121 cm³.

Pulsograms of the milking machine operation with the developed collector were constructed, and the operating strokes for the inter-wall and teat chambers of the milking cup were determined: $t_1 = 0.16$ s, $t_2 = 0.33$

s, and $t_3 = 0.116$ s. At these intervals, the vacuum pressures assume the following values: $P_{oper} = 39$ kPa and $P_{min} = 20$ kPa.

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АНАЛІТИЧНІ ДОСЛІДЖЕННЯ КОНСТРУКТИВНО-РЕЖИМНИХ ПАРАМЕТРІВ КОЛЕКТОРА АДАПТИВНОГО ДОЇЛЬНОГО АПАРАТА

У статті розглянуто проблему підвищення ефективності машинного доїння за рахунок удосконалення конструкції колектора доїльного апарата з урахуванням фізіологічних особливостей тварин. Показано, що більшість серійних колекторів працюють за фіксованими режимами та не *забезпечують індивідуальної адаптації параметрів вакуумної дії до змін інтенсивності молоковіддачі, що може призводити до зниження повноти видоювання, подовження тривалості доїння та негативного впливу на стан вимені.*

Метою дослідження є розроблення конструкції адаптивного колектора доїльного апарата та аналітичне обґрунтування його конструктивно-режимних параметрів, які забезпечують стабільне транспортування молочно-повітряної суміші й оптимальні умови доїння. Об'єктом дослідження є процес функціонування колектора в складі двотактного доїльного апарата, предметом – взаємозв'язки між його геометричними параметрами та режимами роботи.

Запропоновано конструкцію адаптивного колектора з додатковими повітряними камерами, мембранно-клапанним механізмом і регульованим дросельним каналом. З використанням аналітичних, розрахунково-графічних та фізико-математичних методів встановлено залежності між діаметром дросельного отвору і витратою повітря, діаметром вихідного патрубка молочного шланга та параметрами молочно-повітряної суміші, а також між режимними параметрами доїльного апарата і об'ємом молочної камери колектора.

Обґрунтовано раціональні значення конструктивних параметрів: діаметр дросельного каналу – 1,1–2,7 мм, діаметр вихідного патрубка молочного шланга – 8–16 мм, об'єм молочної камери – 121 см^3. Побудовано пульсограми роботи доїльного апарата з розробленим колектором та визначено тривалості робочих тактів і рівні вакуумного тиску. Отримані результати підтверджують доцільність застосування адаптивного колектора для підвищення швидкості доїння, стабільності вакуумного режиму та покращення умов експлуатації доїльних установок.

Ключові слова: *доїльний апарат, адаптивний колектор, вакуумний режим, молочно-повітряна суміш, пульсація, машинне доїння.*

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