DEVELOPMENT OF A DEVICE FOR CLEANSING COW UDDER TEATS AND TESTING IT UNDER INDUSTRIAL CONDITIONS

Preparing cows for milking is one of the most important operations. Not only the speed of milk production but also the quality of milk depends on the level of the work performed.

One of the most effective ways to mechanize the preparation of cows for milking implies the development of a special mechanical brush that cleans and stimulates the teat skin. As a result, there is no need to use additional foam detergents and napkins to cleanse and disinfect teats.

A device has been designed for cleansing teats with two rotating brushes.

Theoretical studies of the interaction of cleansing elements of the device for mechanical removal of pollutants from the udder teats in the course of milking operation were carried out. Assuming constancy of the modulus of elasticity, shape and roughness of teats, linear and angular velocities of brushes, nap stiffness, and homogeneity of physical and mechanical properties of contaminants on the teat, dependence of force F_e of the mechanical device on length l of the cleansing element and its speed ω was established. Under the condition that force F_e of the mechanical device is smaller than force F_p which causes pain but greater than the force retaining pollutants (adhesion), values of the main design and technological parameters of the developed device were determined: $l=8$ mm, $\omega=106$ rpm.

As a result of production tests, it was found that when using the developed device, the daily milk yield of the experimental group of cows exceeded that of the control group by an average of 1.1 times which has made it possible to obtain a supplement of 132.5 kg of milk. Along with this, there was a 0.19 % increase in milk fat content in the experimental group compared to the control group. The number of microorganisms decreased 2.2 times and the number of contaminant particles decreased 4.6 times

Keywords: udder teats, cleansing process, cleansing device, device parameters, bacterial contamination

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1. Introduction

Increasing the efficiency of technological processes of producing livestock products is one of the most significant topical issues of the agro-industrial complex. Reserves of increasing cow's milk yield should be sought for in improving the milking process and application of more advanced methods of organizing activities of machine milking operators [1].

Analysis of numerous experiments [2–5] shows that high-quality and safe milk can be obtained only with strict observance of all sanitary and hygienic requirements during its production and processing. One of such requirements consists in eliminating the possibility of bacterial contamination of the product during milking. That is, it is necessary to eliminate the likelihood of microbial contamination of milk at the initial stage of its production, that is, during milking.

Mechanical cleansing of cow udder teats is one of the constituent processes in the «man-machine-animal» system which are of great interest today. This process is time-consuming and dangerous for its executor [6].

Preparing a cow for milking is an important step that needs to be given due attention. It is impossible to milk a cow without preparation as it is impossible to milk the udder completely in this case. At the same time, there is a high probability of harming the animal.

The variety of techniques for keeping cows bring about various tasks when sending animals for milking using a variety of technical and technological solutions. In particular, there is a problem of spoiling milk quality caused by the imperfection of the algorithm and devices used for preparing cows for milking.

With the use of bedding materials, the udder teats become even dirtier and it gets more difficult to clean them. Existing devices in this case do not provide effective cleansing of teats before milking which leads to an increase in mechanical and microbiological contamination of milk. Mechanical contamination means ingress of not only litter but also particles of other contamination, e. g. manure or protein particles. Milk is mainly contaminated with mixed fodder. Silage particles, milk clots, and animal wool strands form the largest shares of mechanical impurities in milk.

Thus, the need for these studies consists in developing an optimal way of influencing the working organs on the udder teats contacting with contaminants, algorithm, and parameters of the cleansing process.

This approach will make it possible to develop a device for cleansing cow udder teats before milking. This will improve the productivity of the milking machines and operator's labor, increase the number of milked cows per hour. In addition, it will increase milk production and improve milk quality, reveal the mechanism of interaction of cleansing elements (nap) with the teat surface which is of both theoretical and practical interest.

2. Literature review and problem statement

Generalization of literature data, as well as experience of advanced farms, indicate high efficiency of increasing milk productivity of cows through the application of intensive methods. At the same time, along with high requirements to animals concerning their fitness for industrial production, development, and implementation of systems of technological and sanitary-hygienic measures at dairy complexes acquires special significance. They help strengthen cattle health, raise the quantity and quality of products [7–9].

Experienced milking operators stimulating milk yield of cows by washing the udder with warm water and massaging before milking achieve optimal delivery of an alveolar portion of milk by the animal. However, such udder stimulation executed by operators takes a lot of time which reduces their productivity [10].

Mechanized treatment of the udder using sanitating devices is one of the methods of preparing cows for milking and obtaining bacterially pure milk.

Analysis of experiments shows that during mechanical treatment of udder teats before milking with the help of special devices, more complete emptying of the animal's udder takes place. Time of machine milking is also reduced by 13.3 %, the productivity of the milking machines increases by 10.4 %, and cow productivity is raised as well [11, 12].

Nerve receptors of the udder skin become excited by tactile influences, that is, during the extraction of first milk squirts at the beginning of milking, the udder washing, massage, attachment of the milking machine cups as well as pulsation of the cup rubber during milking. To achieve optimal stimulation, it is necessary that the duration of a certain combination of previous operations is at least 60 s [13–15]. Since most operations are manual, they need to be reduced in time to achieve higher productivity of the milking operator labor in automated milking processes. The absence of the stimulation occurring in this way can be compensated only by increasing the stimulating effect of the cleansing devices and pulsation of the teat cup rubbers [16].

The authors of [17–19] claim that udder hygiene is one of the obligatory principles of proper care of cows in order to maintain a high level of milk yield and productivity. Many studies prove that the process of pre-milking treatment of a cow's udder significantly reduces the degree of invasion of primary bacteria into the udder nipple canal. Thus, the udder pre-treatment is the most effective way to prevent cattle milk gland diseases.

Studies [20, 21] confirm the importance of preparatory operations during machine milking which stimulates the intensity of milk production and improves the hygienic quality of milk. Adherence to all the rules of preparation of cows for milking makes it possible to increase the rate of milk production by 0.14–0.36 l/min. At the same time, up to 10–25 % of milk is lost because of insufficient treatment of the udder before milking [22]. For example, a thin film that remains on the udder and teats after treatment creates an obstacle for air passage in the milking cup through skin folds. This increases the level of vacuum which compresses teats leading to constriction of the milk duct, «creeping» of the milking cup to the teat base, injury, appearance of a red inflammatory ring at the teat base, and bacteria penetration into the udder.

Studies of performance properties of the means for mechanical cleansing cow teats were carried out with previously known parameters. This excluded the possibility of establishing patterns of influence of the milking machine parts on the cow's body [23, 24].

Many works are devoted to designing devices for mechanical cleansing and sanitation of udder teats. For example, when comparing the two procedures for preparing the cow udder for milking, it was noted in [25] that the existing technical means are too difficult to apply. The study proposed treatment of teats with a stream of warm water which is very expensive and has low efficiency. This conclusion was reached by scientists in [26, 27]. At the same time, these studies indicate low efficiency of the existing means of mechanical cleansing of udder teats, emphasize the low quality of massage. As a result, all this leads to low stimulation of milk production. Also, the studies point out tools that have significant energy consumption and are difficult to manipulate.

The study [28] provides an analysis of preparatory operations for milking and the methods for evaluating their

effectiveness. For example, devices of preparation for milking, their features of application were presented. Disadvantages of these technical solutions include the high power consumption, low quality of cleansing because of the use of low-quality materials in the devices. Contact with teats is incomplete which indicates that the size of teats of present-day breeds of highly productive animals was not taken into account. Emphasis is placed on the need for further mechanization of preparatory operations.

Therefore, the existing designs of the devices do not provide acceptable conditions for skin cleansing. There is no cleansing system, the devices have weak mechanical strength. Thus, the creation of a suitable device is one of the promising ways to improving the process of cleansing the udder teats. This technical means must meet the following criteria: cause a stable lactation reflex and provide high-quality cleansing of the udder teats from contamination. In addition, it should promote the production of milk with the lowest content of microorganisms and mechanical contaminants and increase the productivity of milking operators.

3. The aim and objectives of the study

The study objective is to develop a device for cleansing cow udder teats with testing in production conditions, which will improve the productivity of animals and product quality.

To achieve this objective, the following tasks were solved:
– develop a design and technological scheme of a technical means of mechanical cleansing of cow udder teats and theoretically substantiate its parameters;
– carry out production tests of the proposed technical solution.

4. Materials and methods used in the study of the technical means for mechanical cleansing of cow udder teats

4. 1. The method used in substantiating the parameters of technical means for mechanical cleansing of cow udder teats

Methods of numerical modeling, parametric synthesis of technical systems using mathematical models of interaction of components in multiphase media, basics of mechanics, laws of molecular physics, integral and differential calculus using methods of system optimization [29, 30] formed the basis of theoretical studies.

The study results were processed using the Mathematica and Microsoft Excel software packages.

4. 2. The procedure of production tests of the technical means for mechanical cleansing of cow udder teats

Two groups of cows were formed in accordance with [31] for the production study of the udder cleansing device. Each group included five cows: experimental and control (daily milk yield: 12–13 kg). The control group was treated in accordance with the technology adopted at the milk complex. In the experimental group, udder teats were cleaned daily.

In order to establish the quality of milk using various techniques of preparation for milking, 3 groups of cows were formed based on the principle of analogs [31]. Groups 1 and 2 were experimental, group 3 was a control. The experiment duration was 94 days. In the first group, udder treatment before milking was performed with HydroOXYPre manu-

factured by Amirakhimprom-Ukraine Co. (Ukraine). The solution composition: Aquadestillata, LauretSulfatisNa, Hydrogeniiperoxydati. At the same time, one of the treatment methods, that is, immersion in special non-rotating glasses was used. The developed device was used in group 2. Udders were treated in the control group before milking with the help of Ankar-imek Co. (Belarus) individual napkins soaked with warm water and squeezed dry.

In order to determine the degree of contamination of the udder surface, rinsing was done with sterile cotton swabs on 2–3 mm thick wooden sticks. Cotton swabs were placed in sterile 5 cm³ tubes of sterile sodium chloride saline so that the swab was 2–3 cm above the liquid level in the tube. Before rinsing, the swab was moistened in saline (excess fluid was removed by squeezing the swab against the inner surface of the upper half of the tube). The surface rinsing was done with the help of a sterile stencil and the swab was again placed in the test tube and immersed in the liquid. Seedings for determining bacterial contamination were performed no later than 3 hours after selection of material from its successive 10-fold dilutions from 10^{-2} to 10^{-6} in physiological saline.

Total bacterial seeding of milk was examined according to [32] based on the property of mesophilic aerobic and optionally anaerobic microorganisms to multiply on dense nutrient agar at a temperature of 30 ± 1 °C for 72 hours.

The total enterobacteria number was determined by seeding milk dilutions and rinsing on Endo medium in the amount of 0.1 cm³ followed by spreading with a spatula. The cultures were incubated for 18–20 hours at 36.5 ± 0.5 °C and then the number of colony-forming units was counted.

The so-called contamination particles belong to foreign substances that get to milk from the environment (Table 1).

Table 1

Contamination of milk with foreign particles

Contamination particles	Particle dimensions
Mixed fodder	130×160 μm
Manure	5×0.3 mm
Silage	10×0.1 mm
Animal's hairs	1,000×5,000 μm

According to various data, the density of contaminant particles is from 1,330 to 1,920 kg/m³. Their presence in milk is undesirable because, in addition to dirt, milk is additionally contaminated with microorganisms leading to its spoilage and impossibility of processing into dairy products.

To determine the purity of milk (for the presence of contaminant particles), OChM-M Rekord device manufactured by EximLab (Ukraine) (Fig. 1) was used.

Fig. 1. General view of OChM-M Rekord device

The device consists of shaped glass, a glass holder, a grid, an arm, and a 250 ml measuring glass.

The principle of operation of the device is as follows. At an initial stage, the device is fixed to a horizontal surface. Next, a rubber tube is attached to the pipe with its other end placed into the container. Then a cotton filter is set so that it completely covers the grid while the cup holder is in the raised position. Then the cup holder is released and it is tightly pressed under the action of the spring force.

The milk to be tested is thoroughly mixed and 250 ml of milk is collected with a measuring cup and poured into the shaped cup. After filtering the portion of milk, the glass holder is tilted, the cotton filter is carefully removed and placed on a sheet of white parchment. The milk purity group was determined by comparing the filter with the approved standard.

Depending on the amount of mechanical impurities (contamination particles) on the filter, the milk is divided into three purity groups by comparing the filter with the standard sample [33] (Fig. 2).

Fig. 3. Diagram of the device for detecting contaminants on the udder teats
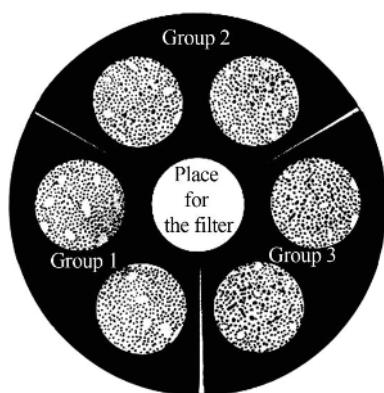

Fig. 4. Detection of udder teat contamination

Fig. 2. The standard for determining milk purity

Group 1 of purity includes milk in which no particles of mechanical impurities are left on the filter. The presence of no more than two particles of mechanical impurities on the filter is allowed for raw milk. The purity group 2: the filter contains individual particles of mechanical impurities (up to 13 particles). Group 3: there is noticeable sediment of particles of mechanical impurities (hairs, particles of fodder, soil, etc.) on the filter.

When determining the presence of contaminants on the udder teats, the procedure of [34] was used for guidance.

The device for detecting contaminants on the udder teats is schematically shown in Fig. 3. It consists of housing 1, cylindrical piece 2, tray 3, filter element 4, sprayer 5, container 6 for distilled sterile water, container 7 for flushing, and mounting 8 for containers.

The method of detecting contaminants on the udder teats under the condition of using the abovementioned device consists of the following (Fig. 4). After preparation of the udder for milking (washing, wiping, massage, milking first streams of milk), the udder teats are treated with distilled sterile water ($t = 40 \pm 2.0\ °C$). Water is applied from a sprayer (10 actuation 1 ml each). A pre-weighed filter element (cotton disk) is placed on an empty sterile receiving container and brought to the place to be treated so that the rinse (distilled water) falls on the filter.

The filter is then dried, weighed again, and compared with the standard. The contamination degree is determined in points. Interpretation of the obtained data was carried out according to Table 2.
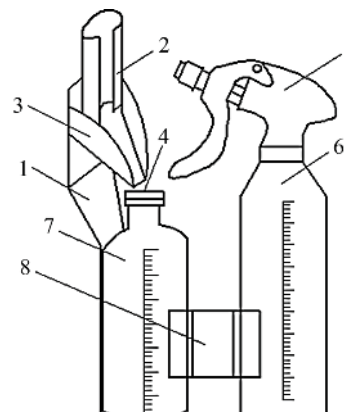
Table 2

Cleanliness of cow udder teats assessed in points

Points	Number of mechanical contaminants on the filter, pcs	Color of the filtering element
I = impeccable	0	white
II = excellent	up to 2	white
III = good	2 to 8	white with inclusions
IV = satisfactory	8 to 13	grayish with inclusions
V = unsatisfactory	more than 13	dirty gray with a multitude of inclusions

Analytical electronic scales AS 60/C (No. 1821-09 in the State Register of Ukraine) with a liquid crystal indicator were used to weigh clean and contaminated samples to determine the contaminant mass.

To assess the efficiency of cleansing the udder teats, the following indicators were used: coefficient K_{tce} which characterizes the teat cleansing efficiency reduced to the initial amount of contamination and the coefficient K_{rua} reduced to the unit area of the teats. Both coefficients are expressed as a percentage:

$$K_{tce} = 1 - \left(m_{id} - m_{fd} \right) / m_{id}\, 100,$$

where m_{id} and m_{fd} are the initial and final degrees of contaminant, respectively, g.

$$K_{rua} = \left(1 - m_{fd-ua} / m_{id-ua}\right)/100,$$

where m_{fd-ua} and m_{id-ua} are the final and initial degrees of contaminant per unit area of the teat, respectively, g/cm^2.

Experimental data were processed using Microsoft Excel application software.

5. The results obtained in studying the technical means for mechanical cleansing of udder teats

5. 1. Substantiation of parameters of technical means for mechanical cleansing of udder teats

The study of the physical process of cleansing the udder teats began with a theoretical substantiation of the interaction of the cleansing elements with contaminants on the teats.

It was noted in studies [35, 36] that a cow begins to feel pain under certain effects of the cleansing element on the udder teat. The action of brush hairs on the cow's teat can be both positive, that is, necessary to remove contamination, and negative, causing damage to the epidermis of the teat skin, destruction of the barrier to pathogens, and pain. This can cause stress to the animal and affect its milking productivity. To avoid this, it is necessary to fulfill the condition under which force F_e of the mechanical device will be less than the force F_p which will cause pain but higher than the force F_a for holding (adhesion) of contamination:

$$F_a \leq F_e \leq F_p. \tag{1}$$

The diagram of the interaction between the cleansing element and the contaminants is presented in Fig. 5.

According to the studies in [37], retention (adhesion) forces can be represented as follows:

$$F_a = c_1 \sigma_{ml} r_k \left(\cos\gamma - \cos\beta\right), \tag{2}$$

where c_1 is an empirical coefficient ($c_1 \approx 1.5$) [37]; σ_{ml} is the surface tension of the drop between the washing solution and the deposit, N/m; r_k is the radius of the contact area of the drop, m [37]:

$$r_k = \sqrt{\frac{24\sin^3\beta\left(\cos\gamma - \cos\beta\right)\sigma_{ml}}{\rho_m g\left(1-\cos\beta\right)^2\left(2+\cos\beta\right)\sin\theta}}, \tag{3}$$

where β, γ are contact angles of the drop, deg; θ is of the teat tilt angle, deg; ρ_m is pollutant density, kg/m^3; g is the acceleration of free fall, m/s^2.
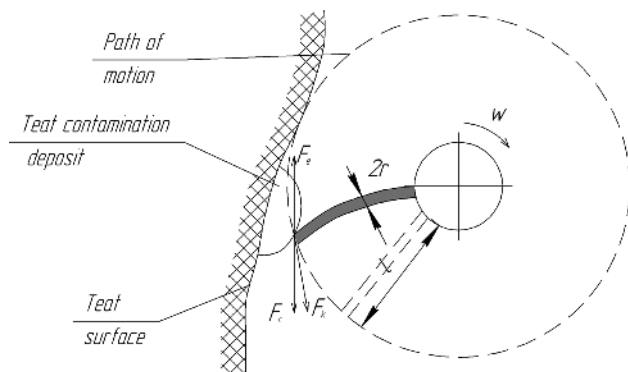
In turn, the force F_e of action of a mechanical device can be divided into two components.

Elasticity force F_k created by one cleansing element can be represented by the expression [38]:

$$F_k = \frac{\pi^2 EI}{4l^2}, \tag{4}$$

where E is the modulus of elasticity of the cleansing element, Pa; I is the axial moment of the cleansing element, m^4; l is the length of the cleansing element, m.

The friction force F_f of the contamination cleansing element can be represented as:

$$F_f = fF_c, \tag{5}$$

where f is coefficient of friction of the cleansing element on the teat; F_c is centrifugal acceleration, H;

$$F_c = m_o \frac{V^2}{l}, \tag{6}$$

where $m_o = \rho_o l \pi r^2$ is the mass of the cleansing element, kg; r is the radius of the intersection of the cleansing element, m; ρ_0 is the density of the cleansing element, kg/m^3; V is the tangential speed of rotation of the extreme point of the cleansing element, m/s. When substituting (2) to (6) in (1), the following is obtained:

$$c_1\sqrt{\frac{24\sin^3\beta\left(\cos\gamma - \cos\beta\right)^3\sigma_{ml}^3}{\rho_m g\left(1-\cos\beta\right)^2\left(2+\cos\beta\right)\sin\theta}} \leq \frac{\pi^2 EI}{4l^2} +$$
$$+ f\rho_o\pi r^2 V^2 \leq F_p. \tag{7}$$

The effect of a nap tuft on the teat tip depends on the linear and angular velocities of the brushes. A cow feels pain at the time of the first touch of the nap tufts of brushes to the tip of the udder teat. These points are K_1 and K_2 (Fig. 6).

Fig. 5. Diagram of interaction between the cleansing element and the pollutant deposits
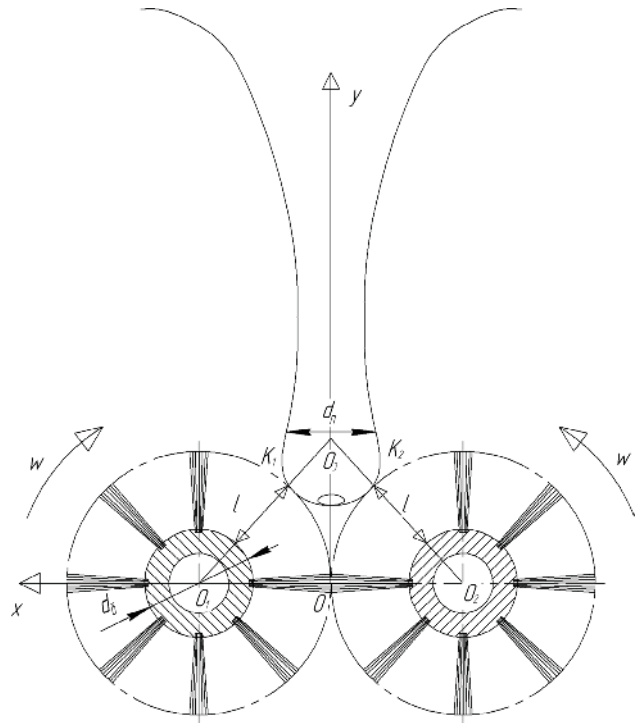

Fig. 6. Diagram of the interaction of brushes and a cow udder teat

Absolute speed V of naps at point 0 of the brush positioning can be represented by the expression:

$$V = \sqrt{\omega^2 \left(l + \frac{d_b}{2} \right)^2 + \left(\frac{L_d}{t_c} \right)},$$ (8)

where L_d is the length of the teats, mm; ω is the angular velocity of rotation of the cleansing element, m/s; d_b is the diameter of the cleansing element shaft, mm; t_c is the duration of cleansing the teat surface, s.

Then inequality (7) takes the final form:

$$c_1 \sqrt{\frac{24 \sin^3 \beta (\cos \gamma - \cos \beta)^3 \sigma_{ml}^3}{\rho_m g (1 - \cos \beta)^2 (2 + \cos \beta) \sin \theta}} \leq \frac{\pi^2 EI}{4l^2} +$$
$$+ f \rho_o \pi r^2 \left(\omega^2 \left(l + \frac{d_b}{2} \right)^2 + \left(\frac{L_d}{t_c} \right) \right) \leq F_p.$$

At an assumption of constancy of the modulus of elasticity, shape, and roughness of the teat, linear and angular velocities of brushes and stiffness of the nap, homogeneity of physical and mechanical properties of the teat contamination, graphical interpretation of dependence of (7) on length of the cleansing element l and rotational speed ω was established (Fig. 7).
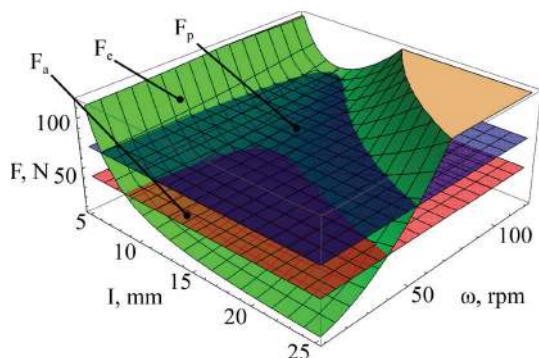

Fig. 7. Dependence of force F_e of the mechanical device on length l of the cleansing element and its rotational speed ω

As can be seen from Fig. 7, at certain values of the cleansing element length l and rotational speed ω, force F_e of the mechanical device is within the value F_p at which pain and force F_a of retention (adhesion) of the contamination will appear. Therefore, for further studies, it is necessary that the value of the force F_e of action of the mechanical device is maximum but less than the value of the force F_p at which pain appears. Take the following values of the main design and technological parameters: $l = 8$ mm, $\omega = 106$ rpm.

According to the theoretically substantiated parameters of the working process of cleansing udder teats from contamination, a device was developed (Fig. 8). Its body is positioned so that two udder teats are between the brushes. At the next stage, the brush drive is turned on and they begin to rotate towards each other performing the operation of forcing first jets of milk, cleansing, and massage.

The theoretical studies that were conducted have made it possible to prepare design documents and make a device for cleansing teats. This device was tested in real production conditions and its feasibility was justified at the next stage.
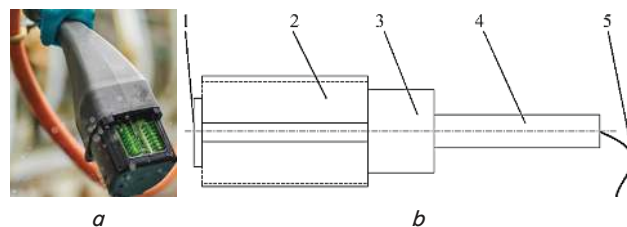

Fig. 8. The device for cleansing udder teats:
a — general view; b — device diagram;
1 — housing; 2 — brushes; 3 — drive;
4 — handle 4; 5 — wire

5. 2. Production tests of the developed device

Data on cow milk yield and changes in milk fat content were statistically processed. The experimental data obtained during 21 days were used to plot the dependence of daily milk yield and milk fat content. The graphs are presented in Fig. 9, 10.

Approximating the obtained data of daily milk yield in a form of the exponential function (Fig. 9), the corresponding confidence intervals $\Delta(Q_1) = 0.12 - 1.55$ kg, $\Delta(Q_2) = 0.16 - 2.48$ kg were calculated with a sufficiently high correlation coefficient, $R(Q_1) = 0.938$, $R(Q_2) = 0.977$. The following results were obtained for daily milk yield: the intensity of its growth for the first 12 days was 13.3 kg in the experimental group against 7.1 kg in the control group.

During the experiment, the daily milk yield in the experimental group exceeded that of the control group by an average of 1.1 times which has made it possible to obtain a supplement of 132.5 kg of milk.

Thus, a significant increase in daily milk yields in the experimental group occurred in the first 9 days of the study: up to 64 kg of milk. Subsequently, the growth of cattle productivity was slow reaching a maximum of 66 kg of milk on the 17th day. Regarding the control group, the maximum daily milk yield was 60 kg on the 17th day.

A noticeable increase in the fat content of milk from cows of the experimental group was observed on days 4–5 of the device use. On average, during the experiment, an increase in milk fat content was 0.19 % for the experimental group compared with the control group. Approximating the obtained data on milk fat content in a form of an exponential function (Fig. 10), corresponding confidence intervals were calculated: $\Delta(\delta_1) = 0.08 - 0.11$ %, $\Delta(\delta_2) = 0.01 - 0.12$ % with a sufficiently high correlation coefficient $R(\delta_1) = 0.959$, $R(\delta_2) = 0.964$.

During the study, the constant growth of milk fat content was noted with the use of a device for preparing cows for milking. The maximum value was observed on the 19th day of the study: 3.57 %. This is explained by the optimal effect of the device on cows taking into account the animal physiology. This shows the positive effect of stimulation of milk production.

As a result of further studies using the device, the milk quality in terms of safety has improved more than 2 times in the experimental group (Table 3).

Thus, in the first half of the studies on the content of MAFAnM in the milk of experimental group 2, the number of microorganisms decreased 1.2 times compared to group 1 and 1.6 times compared to the control group 3.

In the second half of the experiments, the number of microorganisms in experimental group 2 decreased by 2.2 times compared to control group 3.
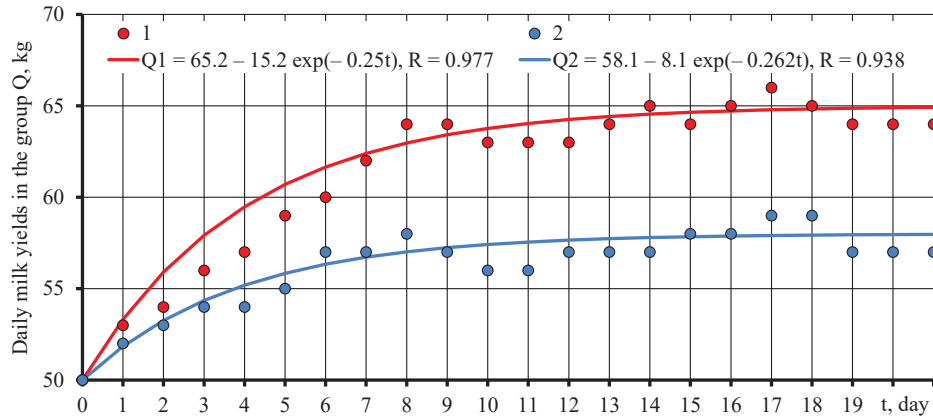
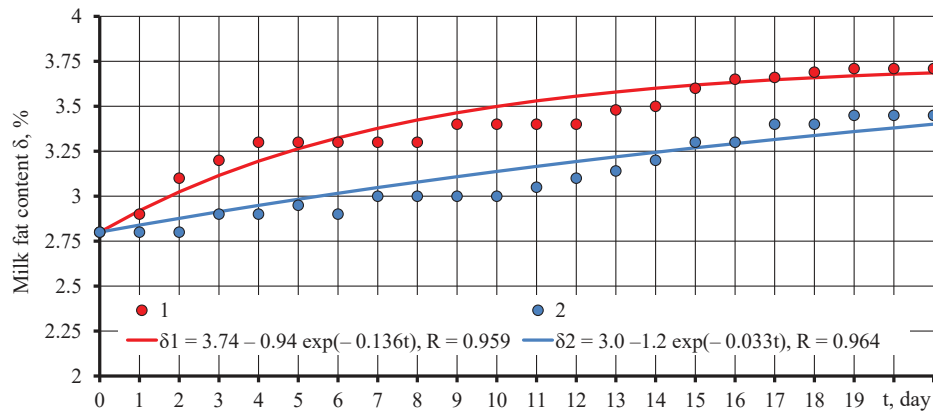Fig. 9. Daily milk yields: 1 — experimental group; 2 — control group

$Q1 = 65.2 - 15.2 \exp(-0.25t), R = 0.977$
$Q2 = 58.1 - 8.1 \exp(-0.262t), R = 0.938$

Fig. 10. Change in milk fat content: experimental group (1); control group (2)

$\delta1 = 3.74 - 0.94 \exp(-0.136t), R = 0.959$
$\delta2 = 3.0 - 1.2 \exp(-0.033t), R = 0.964$

Table 3

Quality of cow's milk and level of contamination of udder teats using various technologies of preparation for milking

Indicator	Requirements of DSTU 7357:2013	Study results		
		Group 1 (experimental)	Group 2 (experimental)	Group 3 (control)
Before the study start				
MAFAnM*, CFU/cm^3	1×10^5	$(3.5\pm0.06)\times10^6$	$(3.4\pm0.04)\times10^6$	$(3.6\pm0.03)\times10^5$
Number of contaminant particles, pcs.	–	3.25±0.36	1.25±0.51	3.41±0.42
Filter weight, mg	–	0.50340±0.00029	0.50022±0.00009	0.50451±0.00037
Weight of mechanical contaminants on the filter, mg/dm^3 (in terms of 1 l of rinse)	–	18.5±4.47	13.6±3.55	21.3±5.43
First half of the study				
MAFAnM*, CFU/cm^3	1×10^5	$(2.6\pm0.05)\times10^5$	$(2.2\pm0.06)\times10^5$	$(34\pm0.08)\times10^5$
Number of contaminant particles, pcs.	–	2.85±0.42	1.14±0.34	3.36±0.81
Filter weight, mg	–	0.50330±0.00075	0.50011±0.00008	0.50410±0.00027
Weight of mechanical contaminants on the filter, mg/dm^3 (in terms of 1 l of rinse)	–	17.4±3.76	12.4±4.33	20.6±8.43
Second half of the study				
MAFAnM*, CFU/cm^3	1×10^5	$(1.8\pm0.07)\times10^5$	$(1.3\pm0.06)\times10^5$	$(2.9\pm0.05)\times10^5$
Number of contaminant particles, pcs.	–	2.19±0.24	0.7±0.18	3.12±0.64
Filter weight, mg	–	0.50210±0.00055	0.50004±0.00008	0.50322±0.00043
Weight of mechanical contaminants on the filter, mg/dm^3 (in terms of 1 l of rinse)	–	16.6±3.41	11.4±2.57	19.3±5.32
K_{tce}, %	–	0.57	0.81	0.49

*Note: * mesophilic aerobic and facultative-anaerobic microorganisms.*

Contamination of udder teats is a combination of manure, urine, and litter. They have different adhesive and cohesive properties. Analysis of contaminant sources and properties of polluting materials have made it possible to classify them. For example, contaminant depends on technological factors: the method of keeping animals, frequency, and quality of aisle cleansing. Teat pollutants are divided according to the aggregate state: liquid, plastically viscous, solid, and dusty. They differ in size, area, thickness, weight and depend on the teat size and shape.

With regard to the pollutant particles, their number in the first half of the study decreased by 2.5 times compared to group 1. Regarding the control group (group 3), this decrease was 2.9 times. In the second half of the study for the number of pollutant particles, an even greater decrease (3.0 and 4.6 times in groups 1 and 3, respectively) was observed.

When determining the level of contamination of teats using the procedure from [34], the filter weight was lowest in the experimental group 2 compared to group 1 and control group 3. The values were as follows: 0.50011 ± 0.00008 mg versus 0.50330 ± 0.00075 and 0.50410 ± 0.00027 mg in the first half of the experiments. In the second half of the experiments, the following values were obtained: 0.50004 ± 0.00008 mg against 0.50210 ± 0.00055 and 0.50322 ± 0.00043 mg.

Regarding the weight of mechanical pollutants on the filter (in terms of 1 liter of rinse from the udder teats), this figure also decreases in group 2 compared to groups 1 and 3. The decrease occurred both in the first and the second halves of the experiments.

Regarding the K_{tce} coefficient which characterizes cleansing efficiency of teats and is reduced to the initial amount of contaminants (Table 3), it had the greatest value in the experimental group 2 (0.81 %). The use of the developed device provided K_{tce} more than 1.4 times compared to group 1 and 1.7 times compared to the control group 3.

Neither inhibitory substances nor pathogens were found in the milk of all groups.

The analysis results show that udder treatment before milking with the help of the developed device provides a significant improvement in quality in terms of safety. There was an improvement in the condition of udder teats.

A bacterial study of the effectiveness of the developed device has found that it provides high-quality cleansing of teats before milking (Fig. 11).

For example, application of the device results in the number of microorganisms decreased 2.2 times and amounted to 1.3 ± 0.06 thousand CFU at $p<0.001$ per 1 cm^2 of the udder teat surface (Fig. 11, b).
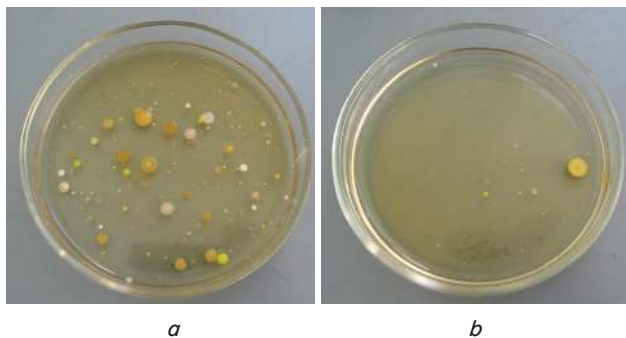

Fig. 11. Bacterial contamination of udder teats:
a — before cleansing; b — after cleansing with the developed device

When analyzing the study results, a high positive correlation was found between levels of bacterial contamination of udder teats and milk ($r=+0.964$).

6. Discussion of the results obtained in studying the technical means for mechanical cleansing of cow udder teats

The initial study stage objective implied the development of a design and technological scheme of a technical means for mechanical cleansing of cow udder teats and theoretical substantiation of its parameters. A diagram of the interaction of the cleansing element with contaminants was developed (Fig. 5). It has made it possible to establish forces acting on the udder teat during its cleansing. Further, a diagram of the interaction of brushes with teats was developed (Fig. 6). Thus, theoretical studies of the interaction of the device cleansing elements with contaminants of udder teats in the course of operation have allowed us to establish the dependence of force F_e of the mechanical device on length l of the cleansing element and its speed ω (Fig. 7).

A device was designed (Fig. 8) according to the theoretically substantiated parameters of the process of cleansing udder teats. The principle of operation of the device consists of the following: position it so that two teats of the udder are between two brushes. Next, actuate the drive of the brushes. Rotating brushes will remove pollutants from the teat surface.

It was found that the intensity of growth of daily milk yield for the first 6 days was 1.33 kg/day in the experimental group of cows against 1.16 kg/day in the control group (Fig. 9). Corresponding confidence intervals $\Delta(Q_1)=$ $=0.12–1.55$ kg, $\Delta(Q_2)=0.16–2.48$ kg were calculated at a sufficiently high correlation coefficient $R(Q_1)=0.938$, $R(Q_2)=0.977$.

There was also a marked increase in milk fat content. On average, during the experiment, an increase in milk fat content was 0.19 % in the experimental group compared to the control group (Fig. 10). Corresponding confidence intervals $\Delta(\delta_1)=0.08–0.11$ %, $\Delta(\delta_2)=0.01–0.12$ % were calculated at a sufficiently high correlation coefficient $R(\delta_1)=0.959$, $R(\delta_2)=0.964$.

As for the contaminant particles, their number decreased 4.6 times with the use of the device in comparison with the control group. The study of the number of microorganisms in the experimental group has found their decreased by 2.2 times compared to the control group (Table 3).

Thus, in contrast to [39] where bacterial contamination of udder teats during milking had an extremely high rate ($<6.5\times10^5$ CFU/cm^3), application of the developed technical means has made it possible to reduce this level to insignificant values ($>1.3\times10^5$ CFU)/cm^3. This was realized due to the effective interaction of cleansing elements of the device with udder teats.

Two methods of udder treatment before milking are most common in dairy farming [40, 41]. To perform the first of them, prior preparation of the solution and clean warm water is required. No less popular way to use udder treatment products consists of immersion of teats in a special container with a disinfectant.

In contrast to [40, 41] where all preparatory work is performed manually, the developed device provides maximum mechanization of the preparatory operations.

As a generalization, it was emphasized in [42, 43] that a process of preparing the cow udder for milking using

various methods and tools is necessary to improve milk yield and hygiene. This idea was confirmed in [44, 45] where it was noted that compliance with sanitary norms during milking with the use of appropriate means had a significant effect. In addition, as noted in [46], the sanitary and hygienic condition of the teat rubber is also important in obtaining quality milk. This is an important area for studies in the overall system of manufacturing high-quality products.

The obtained results complete the problem part which concerns mechanization of preparatory operations for milking, namely treatment (cleansing) of udder teats before milking. This is due to the device parameters ($l=8$ mm, $\omega=106$ rpm) which ensure its efficiency.

The study disadvantages: it does not take into account a number of materials from which the brush element of the device can be made. The geometry of brushes was not taken into account as well.

The study results are consistent with other authors' studies performed earlier in the field of designing tools for dairy farming [12, 47–51] and complement them. An essential feature of this study methodology consists in the fact that the parameters affecting the efficiency of cleansing teats were taken into account as much as possible. This creates an opportunity to study and justify the optimal parameters of the device for cleansing udder teats. In addition, because of the significant variability of the cleansing device design parameters, there are difficulties in the overall solution of optimal action of its cleansing elements to satisfy the physiological needs of animals in the process of contaminant removal. This remains an unresolved issue in the technology of milk production.

The effectiveness of present-day milking equipment depends to a large extent on compliance with specified sequence, continuity, and duration of the milking operations. They are determined by the physiological functions of the udder and design features of the milking equipment. This solution to the problem of cleansing udder teats takes into account the physiological characteristics of animals and fits harmoniously into the overall milking process.

The conducted studies have resulted in a set of new provisions which consist in the development of a mathematical model of cleansing the cow udders with the help of this device. The mathematical model establishes a relationship between parameters of action of the cleansing nap on the teat contaminants, the brush device and cleansing conditions.

The study results form a basis for the creation of optimized, more physiologically fit options for milk production technologies as well as devices for cleansing animals' skin.

The studies aimed at revealing the mechanism of influence of the cleansing elements made of various materials and with various design (geometrical) parameters on udder teats can be considered promising. This will expand the understanding of the interaction of cleansing elements with udder teats and improve the efficiency of the cleansing devices. All this will raise the productivity of cattle and the activities of cattle farm personnel.

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7. Conclusions

1. Assuming constancy of the modulus of elasticity, shape, and roughness of udder teats, linear and angular velocities of brushes and nap stiffness, homogeneity of physical and mechanical properties of teat contaminants, the dependence of force F_e of the mechanical device on length of the cleansing element l and its speed ω was established. Values of the main design and technological parameters of the developed device were determined ($l=8$ mm, $\omega=106$ rpm) for the condition under which effort F_e of the mechanical device action is smaller than the force F_p which causes pain but larger than the force F_a retaining the contaminant (adhesion).

2. Application of the designed device has made it possible to obtain a 132.5 kg increase in milk yield, a 0.19 % increase in fat content, a 2.2-time decrease in the number of microorganisms, and a 4.6 times less number of contaminant particles. The filter weight in determining the level of teat contamination in experimental group 2 had the lowest value compared to that of group 1 and control group 3 during all experimental periods ($0.50011\pm0.00008-0.50004\pm0.00008$ mg).

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