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JUSTIFICATION OF THE MODES OF THE MILK WASHING SYSTEM OF THE MILKING INSTALLATION

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Abstract. The process of washing the elements of milking machines is one of the most important technological operations, the efficiency of which depends on the level of primary contamination of milk. The purpose is to investigate the operating parameters of the air injector operation of the milkweed flushing system of the milking plant and to substantiate their rational values.

As a result of numerical modeling in the software package STAR-CCM+ and because of numerical simulation and experimental studies of the process of washing the milking line of the milking plant using an injector, the dependence of changes in the velocity of the milk and the degree of purity of the milk line at different values of its diameter from the working vacuum pressure, the duration of the interval injection of the air injector and the duration of the pause of the air injector.

Comparing the theoretical and experimental dependences of the Fisher pressure velocity change, the Pearson correlation coefficient and the determination coefficient can confirm the adequacy of theoretical studies.

Solving the compromise problem, which minimizes the value of the rate of change of pressure at the highest value of the degree of purity of the milk line for different values of the diameter of the milk line were obtained the corresponding rational parameters of the modes of operation of the injector.

Key words: milk, milking machine, washing, modes, numerical modeling, experimental studies.

INTRODUCTION

As a result of long-term operation of milk-producing lines of milking machines on their internal surfaces various in composition, properties, thickness, strength of adhesion to the surface of deposition of alkaline and acid nature are formed. Their presence leads to bacterial contamination of milk, resulting in a decrease in its quality and shelf life (Ushakov *et al.* 2014). These deposits are formed due to inefficient washing of milking equipment (Kartashov *et al.* 2010). Therefore, the process of washing the elements of milking machines is one of the most important technological operations, the effectiveness of which depends on the level of primary contamination of milk.

ANALYSIS OF RECENT STUDIES AND PUBLICATIONS

Analysis of literature sources has shown that despite the difference in the quantitative characteristics of the process of washing milking machines (temperature, duration) as a whole in the composition of operations and the sequence of their execution, there exists currently a consensus, namely (Ushakov *et al.* 2014):

– preliminary rinsing and removal of milk residues with warm water (30-48 °C) for 2-10 minutes;

– preparation of washing alkaline liquids in hot water at a temperature of 60-70 °C and washing for 15-30 minutes;

– rinsing and removing residual cleaning liquids with warm or hot water for 10 minutes;

– washing 1-2 times a week with acid cleaning liquids;

– flushing the system before starting with hot water and disinfectant liquids;

– treatment of communications with acidic liquids with a temperature of 60-70 °C for the removal of milk stone is carried out after prerinsing, followed by an intermediate rinse with hot water at a temperature of 70 °C for 5 minutes, and then washed with an alkaline liquids.

To increase the efficiency of washing milking equipment, systems with the spontaneous formation of cortical fluid and air flow (Berezutsky *et al.* 2000) are used. The latter is implemented using air injectors. However, the modes of their work have not been fully explored, both theoretically and experimentally.

PURPOSE AND RESEARCH

Investigate the operating parameters of the air injector of the milking system flushing milking device parts and to substantiate their rational values.

MATERIALS AND METHODS OF RESEARCH

The study of the process of operation of the milk system flushing process with an air injector was carried out in two stages.

The first stage was performed on the basis of numerical simulation in STAR-CCM + software package (Ushakov *et al.* 2014). The scheme of numerical experiment is presented in Fig. 1. Milking line of the milking device is a straight horizontal pipe with a length of L = 5 m. On the right side on top is mounted an injector with a diameter of D_m = 10 mm. The continuum of the milking line of the milking device was formed on the basis of a surface net mesh generator and a multifaceted cell generator. The basic net mesh size was 0.001 m.

The numerical simulations were performed on the basis of the following physical models: multiphase interaction, isothermal fluid energy equation, gravity field, k-ε turbulence model, averaged according to Reynolds parameters, Noaye-Stokes equation, separated flow, multiphase state equation, fluid volume (VOF) , Euler multiphase.

It was assumed that the detergent liquid during the movement had a constant density of ρ_f = 997.6 kg/m^3, the dynamic viscosity was μ_f = $8{,}88 \cdot 10^{-4}$ Pa s. The milk also had a constant density of ρ_m = 1027 kg/m^3 in the course of movement, and its dynamic viscosity was μ_m = $2{,}72 \cdot 10^{-3}$ Pa·s. The air obeyed the ideal gas equation. The dynamic viscosity of air was μ_g = $1.85 \cdot 10^{-5}$ Pa·s, molecular weight 28.9 kg/moll (Tsoi *et al.* 2007).

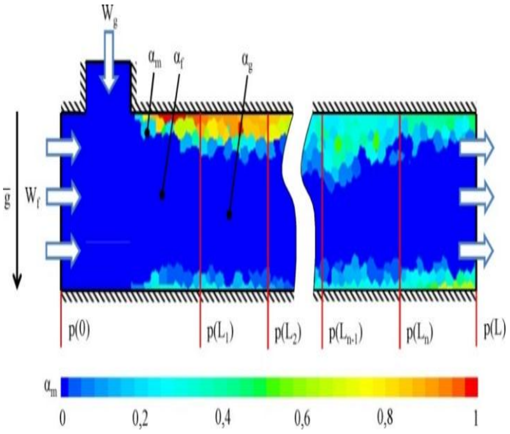

Figure 1. Schematic diagram of the numerical experience of the process of motion of a multiphase medium on a horizontal milk line of a milking device

Initially, it was assumed that the entire volume of the horizontal straight line was filled with milk, ie α_m = 100%. The vacuum pressure was p = 45 kPa. Further, a mass airflow W_f = 0.001 kg/s was performed on the left boundary, a constant vacuum pressure p (L) = 45 kPa on the right one, and the injector nozzle was completely closed.

After 16 s (time was selected from the condition of stabilization of the milk and air content in the volume of the milk line), the air flow stopped. Instead, a mass flow of the washing solution W_f = 0.2 kg/s was performed on the left border. Starting at 17 s, the injector periodically closes (1 s and 9 s) and opens (1 s and 9 s), combining the internal volume of the milk mixture with atmospheric pressure and letting the air into the milk line.

The factors of the studies were the diameter of the milk line D_m, the working vacuum pressure p_w, the duration of the injection time of the air injector t_{inj}, the duration of the pause of the air injector t_p. The boundaries and intervals of research factors are presented in Table. 1.

In the process of numerical modeling, the dynamics of vacuum pressure at the distance from the left boundary were determined (p (0 m), p (1 m), p (2 m), p (3 m), p (4 m), p (5 m) and the dynamics of the content of the components of the multiphase medium (washing solution α_f, air α_g, milk α_m).

A qualitative criterion for the evaluation of studies of the modes of operation of the milk flushing system of milk-milking equipment with an air injector is the average value of the layer of milk on the pipe wall h_m, which was determined by the formula

$$h_m = \frac{D_m}{2}\left(1 - \sqrt{1 - \frac{\alpha_m}{100}}\right). \tag{1}$$

Table 1 – Limits and intervals of numerical modeling factors

Level	The diameter of the milk line D_m, mm (x_1)	Working vacuum pressure p_w, kPa (x_2)	The duration of the injection cycle of the air injector t_{inj}, s (x_3)	Pause time of the air injector t_p, s (x_4)
Upper (+1)	70	75	9	9
Middle (0)	60	60	5	5
Lower (–1)	50	45	1	1
Interval	10	15	4	4

The smaller was the thickness of the layer of milk on the wall of the milk line h_m, the better the washing process was performed.

The simulation was performed by alternating all levels of factors with a total of $3^4 = 81$ experiments. Then, using the Wolfram Mathematica software package, a second-order regression model was determined for each of the proposed criteria.

The second experimental stage was carried out on the basis of a laboratory milking machine with available upper and lower milk ducts with a flushing apparatus manufactured by JSC "Bratslav".

The scheme of the experimental stand is presented in Fig. 2.

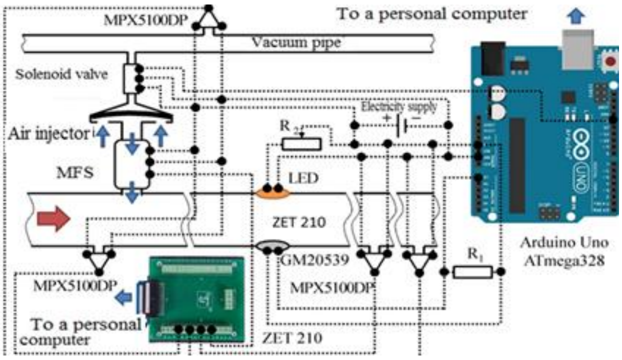

Figure 2. Diagram of an experimental stand for investigating the operating modes of the air injector of the milking system flushing milking device

The stand booth includes: a laboratory of milking machine (including a milk line and a vacuum line); air injector, solenoid valve; MFS - mass flow sensor; four MPX5100DP vacuum pressure sensors, three of which are located on a milk line 2 m apart and one is a vacuum wire, and are connected to the ADC / DAC module ZET 210; a milk sensor for detecting contamination of a milk line consisting of LED 1W 100 Lm, photoresistor GM20539, resistor R_1 = 10 kΩ, adjustable resistor R_2 = 5 kΩ, control boards ArduinoUno ATmega328; Power Supply.

The general view of the experimental stand booth is presented in Fig. 3.

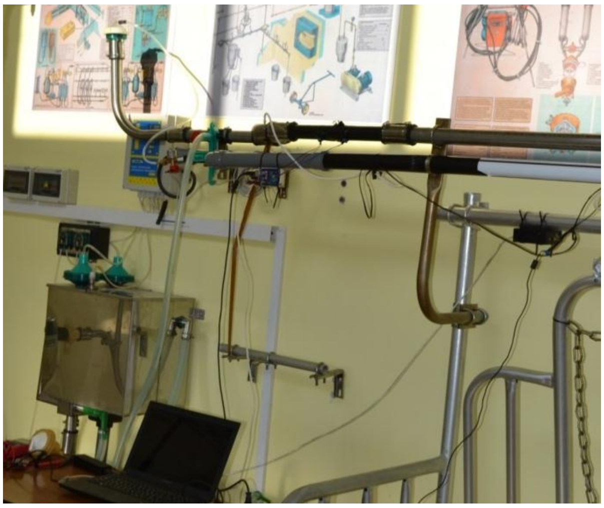

Figure 3. General view of the experimental stand booth for investigating the operating modes of the air injector of the milking system flushing milking device

The factors of the experimental studies are the working vacuum pressure p_w, the duration of the injection time of the air injector t_{inj}, the duration of the pause of the air injector t_p and the volume flow rate of air through the air injector Q_V. The boundaries and intervals of research factors are presented in Table. 2.

Table 2 − Limits and intervals of experimental research factors

Level	Working vacuum pressure p_w, kPa (x)	The duration of the injection cycle of the air injector t_{inj}, s (x)	Pause time of the air injector t_p, s (x)	Volume air flow through an air injector Q_V, l/min (x)
Upper (+1)	75	9	9	300
Middle (0)	60	5	5	200
Lower (–1)	45	1	1	100
Interval	15	4	4	100

The working vacuum pressure p_w is set on a laboratory milking machine using a vacuum regulator and is controlled by the MPX5100DP vacuum pressure sensor.

The error level of measuring the vacuum pressure within the test range is ± 0.1 kPa.

The duration of the t_{inj} injection and pause times of the t_p air injector is set using the solenoid valve that is connected to the ArduinoUno ATmega328 control board. The error level of the injection and pause cycles is ± 1 ms.

The volumetric air flow rate through the Q_V air injector is determined by closing the openings on the air injector and is controlled by the BOSH 280218037 FMS sensor.

Before each experiment, the photo sensor was removed from the laboratory milking machine, washed, wiped and immersed in a container with milk, where it was stored for 20 min.

Next, the study factors were set at the required level and the washing machine was started in continuous rinsing mode for 30 min.

In the course of the experimental studies, the dynamics of the vacuum pressure at each of the connected sensors (p_0, p_1, p_2, p_3) and the dynamics of the resistance change on the photo sensor R_f were determined.

A qualitative criterion for evaluating studies of modes of operation of the milking system flushing system with an air injector is the degree of purity θ_{milk}, which is defined as the change in the average value of the layer of milk h_{milk} on the pipe wall:

$$\theta_{milk} = 100 \frac{h''_{milk} - h'_{milk}}{h'_{milk}}. \quad (2)$$

where h'_{milk} – initial value of the thickness of the layer of milk on the pipe wall, m;

h''_{milk} – the final value of the thickness of the layer of milk on the pipe wall, m.

According to previous laboratory studies (Shevchenko *et al.* 2013) the thickness of the layer of milk on the wall of the tube was determined taking into account the value of the resistance on the photo sensor according to the formula

$$h_{milk} = \frac{1}{k_{\lambda milk}} \ln\left(\frac{R_f}{R_0}\right). \quad (3)$$

where R_f – the current value of the resistance on the photo sensor, Ohm;

R_f – the initial value of the resistance on the photo sensor, Ohm;

$k_{\lambda milk}$ – indicator of light absorption by milk, which was determined as a result of laboratory tests (Coj *et al.* 2005), m^{-1}.

The criterion that limits the operating parameters of the milking system of the milking device with the air injector is the value of the change in pressure at the injection frequency and the pause of the air injector (rate of change of pressure) $\frac{\Delta p}{\Delta t}$, which is calculated by the formula

$$\frac{\Delta p}{\Delta t} = \frac{p_{max} - p_{min}}{t_{inj} + t_p}. \quad (4)$$

The greater the rate of change in pressure in the milking system of the milking plant, the greater the likelihood of an unmanaged hydraulic shock that will destroy not only the layer of milk and milk deposits on the surface of the wall of the milk line, but also the milk line itself.

Therefore, the rational modes of operation of the milking system flushing system with an air injector can be achieved by minimizing the value of the layer of milk on the wall of the milk line, the minimum allowable washing time and the rate of change of pressure.

Experimental studies were conducted according to the Hartley-Kono plan (Na-Co4) for four factors at three levels with a total of 18 experiments (Aliyev *et al.* 2011). Then, using the Wolfram Mathematica software package, a second-order regression model was determined for each of the proposed criteria.

RESEARCH RESULTS

As a result of the first stage, namely numerical modeling and further processing of the received data in the software package Wolfram Mathematica, the dependence of the change in the value of the thickness of the layer of milk based on the factors of research was obtained in the form

$$\begin{gathered} h_m = 0{,}87386 - 0{,}0378379\ D_m + \\ 0{,}000609942\ D_m^2 + 0{,}013656\ p_w - \\ 0{,}000488142\ D_m p_w + 0{,}000135725\ p_w^2 - \\ 0{,}02288\ t_{inj} + 0{,}0001143\ D_m t_{inj} + \\ 0{,}00285755\ t_{inj}^2 - 0{,}0324547\ t_p + \\ 0{,}000305141\ D_m t_p - 0{,}00114002\ t_{inj} t_p + \\ 0{,}00381425\ t_p^2. \end{gathered} \tag{5}$$

Having the result of dependency (5) it is established that the larger the diameter of the milk line used in the milking machine, the higher the vacuum pressure should be created to ensure the quality of its walls from the milk residue. The duration of injection of the air injector t_{inj} and the duration of the pause of the air injector t_p should be in the range of 2.9-3.6 s and 1.9-2.8 s, respectively.

The recalculation of equation (5) by the formula (2) makes it possible to determine the theoretical dependence of the change in the degree of purity θ_{milk} on the research factors:

$$\begin{gathered} \theta_{milk} = 12{,}614 + 3{,}78379\ D_m - \\ 0{,}0609942\ D_m^2 - 1{,}3656\ p_w + \\ + 0{,}0488142\ D_m p_w - 0{,}0135725\ p_w^2 + \\ 2{,}288\ t_{inj} - 0{,}01143\ D_m t_{inj} - \\ - 0{,}285755\ t_{inj}^2 + 3{,}24547\ t_p - \\ 0{,}0305141\ D_m t_p + \\ + 0{,}114002\ t_{inj} t_p - 0{,}381425\ t_p^2. \end{gathered} \tag{6}$$

A graphical interpretation of the theoretical dependence (6) at D_m = 50 mm is presented in Fig. 4.

As a result of numerical simulation and further processing of the obtained data in the Wolfram Mathematica software package, the dependence of the pressure change on the injection frequency and the pause of the air injector (the rate of change of pressure) on the research factors is shown in the form

$$\begin{gathered} \frac{\Delta p}{\Delta t} = 37{,}6294 - 0{,}226911\ D_m + 1{,}75826 \\ p_w - 0{,}00763316\ p_w^2 - \\ - 15{,}3799\ t_{inj} - 0{,}0737435\ p_w t_{inj} + \\ 1{,}01054\ t_{inj}^2 - 3{,}37464\ t_p - \\ - 0{,}0442911\ p_w t_p + 0{,}925824\ t_{inj} t_p - \\ 0{,}0872651 t_p^2. \end{gathered} \tag{7}$$

A graphical interpretation of the theoretical dependence (7) at D_m = 50 mm is presented in Fig. 5.

As a result of the second stage, namely experimental studies and further processing of the obtained data in the software package Wolfram Mathematica, the dependence of the change in the degree of purity θ_{milk} on the research factors is shown in the form

$$\begin{gathered} \theta_{milk} = 29{,}5872 + 1{,}42395\ p_w - \\ 0{,}0155436\ p_w^2 + 0{,}0640533\ Q_V - \\ - 0{,}0000718187\ p_w Q_V + 0{,}000110483 \\ Q_V^2 - 0{,}121902\ t_{inj} - \\ - 0{,}00398034\ p_w t_{inj} + 0{,}000214527\ Q_V t_{inj} \\ - 0{,}080346\ t_{inj}^2 + 1{,}64717\ t_p + \\ + 0{,}00567526\ p_w t_p + 0{,}00148151\ Q_V t_p + \\ 0{,}129843\ t_{inj} t_p - 0{,}389542\ t_p^2. \end{gathered} \tag{8}$$

Graphical interpretation of theoretical dependence (8) at Q_V = 100 l/min. is presented in Fig. 4.

The analysis of Figure 4 and the dependencies (6) and (8) makes it possible to confirm the variability of the injector operating modes. Thus, as the working vacuum pressure p_w increases, the degree of purity of the θ_{milk} milk line increases. This observation is quite logical, as the interaction of the shock wave resulting from the pulsations of the vacuum pressure with the layer of milk on the walls of the milk line increases. For the duration of the injection cycles t_{inj} and pause t_p of the air injector, an optimum is observed at which the degree of purity of the θ_{milk} milk line is at its maximum. At the lowest stroke rates, the speed of propagation of the shock wave is high, which leads to a decrease in the speed of its interaction with the layer of milk on the walls of the milk line. At the highest values of strokes the magnitude of the shock wave is not large, which leads to less destructive action on the layer of milk, which is placed on the walls of the milk line.

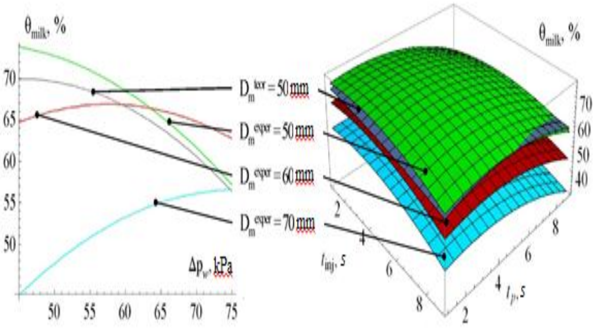

Figure 4. Dependence of the value of the purity of the milk line θ_{milk} on the working vacuum pressure p_w, the duration of the injection cycle of the air injector t_{inj} and the duration of the pause of the air injector t_p

Comparing theoretical (6) and experimental (8) dependences according to Fisher's criterion $F = 1{,}88 < F_{0{,}05}$ (17; 26) = 2.04, Pearson correlation coefficient r = 0.98 and coefficient of determination $R^2 = 0.96$ can be asserted the adequacy of theoretical studies.

As a result of experimental studies and further processing of the obtained data in the software package Wolfram Mathematica, the dependence of the change in pressure on the injection frequency and the pause of the air injector (the rate of change of pressure) from the research factors is shown in the form

$$\frac{\Delta p}{\Delta t} = -9{,}25598 + 2{,}04533\, p_w - 0{,}0117884\, p_w^2 + 0{,}145057\, Q_V - 12{,}0428\, t_{inj} - 0{,}0504414\, p_w t_{inj} + 0{,}796128\, t_{inj}^2 - 4{,}45978\, t_p - 0{,}0270083\, p_w t_p + 0{,}812068\, t_{inj} t_p. \quad (9)$$

A graphical interpretation of the theoretical dependence (9) at $Q_V = 100$ l/min is presented in Fig. 5.

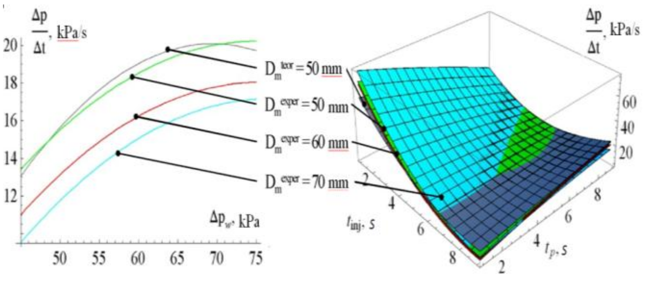

Figure 5 Dependence of pressure change rate value $\frac{\Delta p}{\Delta t}$ from the working vacuum pressure p_w, the duration of the injection cycle of the air injector t_{inj} and the duration of the air injector pause t_p

With the increase of the working vacuum pressure p_w and the duration of the pause of the air injector t_p, the rate of change of pressure increases. Conversely, with the increase in the duration of injection of the air injector t_{inj}, the rate of pressure change decreases.

Comparing theoretical (7) and experimental (9) Fisher's criterion dependences $F = 1{,}15 < F_{0{,}05}$ (17; 26) = 2,04, Pearson correlation coefficient r = 0,99 and determination coefficient $R^2 = 0{,}98$ can be asserted the adequacy of theoretical studies.

Due to the fact that the rational parameters of theoretical (6) *s* (7) and experimental (8) - (9) dependencies differ, it is necessary to solve the compromise problem, which is reduced to minimize the value of the rate of change of pressure at the highest value of the degree of purity of the milk:

$$\begin{cases} \theta_{milk}^{teor.}(D_m, p_w, t_{inj}, t_p) \to \max, \\ \theta_{milk}^{exper.}(p_w, t_{inj}, t_p, Q_V) \to \max, \\ \left(\frac{\Delta p}{\Delta t}\right)^{teor.}(D_m, p_w, t_{inj}, t_p) \to \min, \\ \left(\frac{\Delta p}{\Delta t}\right)^{exper.}(p_w, t_{inj}, t_p, Q_V) \to \min. \end{cases} \quad (10)$$

Solving the system of equations (10) in the software package Wolfram Mathematica for different values of the diameter of the milk line, we obtain the corresponding rational parameters of the modes of operation of the injector:

at D = 50 mm → $p_w = 45{,}0$ kPa, $t_{inj} = 6{,}1$ s, $t_p = 3{,}8$ s, $Q_v = 300$ l/min, (11)

$$\theta_{milk} = 92{,}3\ \%,\ \frac{\Delta p}{\Delta t} = 42{,}0\ \text{kPa/s};$$

at D = 60 mm → p_w = 45,0 kPa, t_{inj}= 6,1 s, t_p = 3,5 s, Q_v =300 l/min,

$$\theta_{milk} = 92{,}1\ \%,\ \frac{\Delta p}{\Delta t} = 42{,}1\ \text{kPa/c};$$

at D = 70 mm → p_w = 60,6 kPa, t_{inj}= 5,9 s, t_p = 3,4 s, Q_v =300 l/min

$$\theta_{milk} = 88{,}4\ \%,\ \frac{\Delta p}{\Delta t} = 40{,}0\ \text{kPa/c}.$$

CONCLUSIONS

1. As a result of numerical simulation in the software package STAR-CCM+ and experimental studies of the process of washing the milk line of the milking device using an injector, we determined the dependence of the change in pressure velocity ΔP/Δt and the value of the degree of purity of the milk line θ_{milk} at different values of its diameter D_m from the working vacuum injection of air injector t_{inj} and duration of pause of the air injector t_p.
2. Comparing the theoretical and experimental dependence of the change in pressure velocity ΔP/Δt according to the Fisher criterion $F = 1{,}88 < F_{0{,}05}\ (17;\ 26) = 2{,}04$, Pearson correlation coefficient r = 0,98 and the coefficient of determination $R^2 = 0{,}9$ can be asserted the adequacy of theoretical studies.
3. Comparing the theoretical and experimental dependence of the degree of purity of the θ_{milk} milk by the Fisher criterion $F = 1{,}15 < F_{0{,}05}\ (17;\ 26) = 2.04$, Pearson correlation coefficient r = 0.99 and the coefficient of determination $R^2 = 0.98$ can be stated the adequacy of theoretical studies.
4. Solving the compromise problem, which minimizes the value of the rate of change of pressure at the highest value of the degree of purity of the milk line for different values of the diameter of the milk line were obtained the corresponding rational parameters of the modes of operation of the injector: when D = 50 mm → p_w = 45,0 kPa, t_{inj} = 6,1 s, t_p = 3,8 s, Q_v =300 l/min, θ_{milk} = 92,3 %, ΔP/Δt = 42,0 kPa/c; at D = 60 mm→ p_w = 45,0 kPa, t_{inj}= 6,1 s, t_p = 3,5 s, Q_v =300 l/min, θ_{milk} = 92,1 %, ΔP/Δt = 42,1 kPa/c; at D = 70 mm → p_w = 60,6 kPa, t_{inj}= 5,9 s, t_p = 3,4 s, Q_v =300 l/min, θ_{milk} = 88,4 %, ΔP/Δt = 40,0 kPa/c.
5. It is worth noting that at the Department of Agricultural Machines of Vinnitsa National Agrarian University, other scientific studies on the mechanization of animal husbandry were conducted. For example, (Hunko *et al.* 2007) − where the results of studies of heat utilizer according to given technological and design parameters are presented.

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Table of contents