

This paper reports the construction of a mathematical model for the process of dosing liquid foods (non-carbonated drinking water). The model takes into consideration the differential equations of changes in the kinematic parameters of the liquid in a dosing device's channels and the corresponding accepted initial and boundary conditions of the process. The boundary conditions account for the influence of software-defined airlift dosing modes using the driver and the geometry of the product pipeline. The current's value measured in mA (with an accuracy of 0.001 mA) relative to the standard scale I_{min} is $I_{max}=4...20$ mA.

Individual stages of the dosing process were analytically described, followed by the analysis of separate stages and accepted assumptions.

The accuracy achieved when testing the experimental sample of the dispenser, with the repetition of the dose displacement process, ranged between 0.35 % and 0.8 %.

The reported results are related to the established dosage weight of 50 ml when changing the initial level of liquid in the tank of the dosing feeder by 10 mm.

An experimental bench has been proposed for investigating the functional mechatronic dosing module under the software-defined modes to form and discharge a dose of the product. The bench operates based on proportional feedback elements (4–20 mA) for step and sinusoidal pressure control laws in the dosing device.

The control model with working dosing modes has been substantiated. The control models built are based on proportional elements and feedback.

During the physical and mathematical modeling, the influence of individual parameters on the accuracy of the product dose formation was determined; ways to ensure the necessary distribution of compressed air pressure, subject to the specified productivity of the dosing feeder, were defined. The study results make it possible to improve the operation of precision dosing systems for liquid products based on electro-pneumatic complexes

Keywords: dose discharge, airlift system, excess pressure, feedback, dosing accuracy

SYNTHESIS OF A PRECISION DOSING SYSTEM FOR LIQUID PRODUCTS BASED ON ELECTRO-PNEUMATIC COMPLEXES

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1. Introduction

Among those enterprises that are associated with the tasks to automate the processes of dosing liquid products, packaging production occupies a special place. This is due to the development of the packaging industry. A number of small and medium-sized enterprises engaged in the production and packaging of liquid products were set up. In this regard, the task to design inexpensive and compact dosing and packing equipment that could replace imported machinery, taking into consideration specific working conditions for small businesses, becomes extremely relevant. Examples include the production of food eco-products, auto cosmetics, perfumery and pharmaceuticals, paints and varnishes, essential and fatty oils with biologically active additives, and many others.

Specific requirements are put forward to the systems for dosing and packing modules of liquid products in containers,

under the conditions of small businesses. For example, high operational reliability, wide range and high dosing accuracy combined with the possibility of prompt reconfiguration of equipment for different types of liquids and dosing ranges. Additionally, take into consideration the possibility of smooth dose adjustment in a wide range; the possibility of prompt rinsing or replacement of the product pipeline; the possibility of mounting the dosing feeder on a conveyor line; the construction of multichannel dosing systems. An important requirement is the absence of droplet formation between operations; compactness, simplicity, and safety of service; fire safety, etc.

The task to automate those dosing operations is complicated if it is necessary to implement a system of automatic adjustment of technological process parameters in non-valve modules in the packing part [1–3].

To address the issues related to packaging liquid products in containers, the most common are dosing devices of

the volume-piston type with measuring chambers of variable volume, and with valve-piston actuators that are proportionally controlled. Additionally, sometimes there are expensive weight-dosing devices manufactured abroad. However, these and other known dosing devices do not fully meet the above requirements and have several fundamental disadvantages that narrow the scope of their application by small businesses. Thus, it is an absolute top task to design reliable, inexpensive, and compact equipment for packing liquid products by small-scale enterprises.

2. Literature review and problem statement

Many processes in the food, chemical, textile, perfume, and many other industries include operations of dosed supply of liquid products. Work [1] investigates product losses, which are set by technological regulations. The process management system provided by the authors of the cited work typically contains only closed circuits for the automated adjustment of basic parameters. Unresolved questions remain regarding the design and implementation of airlift mechatronic dosage systems with tracking circuits involving two or more technological parameters. Critical analysis of precision liquid food dosing systems based on electro-pneumatic systems is complicated by the absence of ready-made industrial actuating modules, in particular, dosing devices [2], for ranges of small doses. These can be difficulties in tracking and reducing energy costs in hydraulic and regulatory structures with small diameters through cross-sections and controlling elements.

The variant of advanced analysis of the task of automation of technological processes of airlift dosage is the designs of servo-pneumatic valves described in [3].

The control object has inertial delay and parametric non-stationarity – this complicates the above description. This can be traced in the variability of its dynamic parameters by the dosage time in the mechatronic module. The option of overcoming the corresponding difficulties may be the results reported in [4]. In that case, high-quality organization of dosing processes is possible only with the use of closed automatic control systems with the ability to re-adjust the implementation of various laws of regulation according to technological parameters. For such an object, as specified in work [5], in addition to the means of automatic control and adjustment of basic parameters, the control system must contain monitoring and control circuits with elements of proportional control. Solving such tasks requires the development of universal systems of automatic dosage that are structurally and functionally adapted for the execution of operations of both portion and continuous dosage [6]. Examples of such solutions are the industrial wastewater treatment systems containing contours of dosed supply of chemical agents [7]. Solving complex problems related to the formation of multicomponent emulsions, as the authors of the cited work note, is a relevant area in the development of synergy of water treatment systems and the design of precision dosing systems.

The disadvantages identified in the cited works [4–7] include the complexity of designs of dosing and control units containing a large number of mechanical moving parts, which leads to a significant decrease in the operational reliability of the equipment. An important disadvantage is the comparative narrowness of the dosage ranges provided and

the inappropriateness of the same type of equipment to the dosage of media with different physicochemical properties. The design of dispensers is also affected by their narrow functionality, reflected in the absence in a number of structures of remote control means of operational reconfiguration and adjustment of their output parameters.

In [8], the reported results of control over the creation of suspensions, involving dosing systems with elements of electro pneumatics, showed the possibility of using control circuits without feedback. However, the questions of the accuracy of the dosage remained uncertain. The results of X-ray photoelectron spectroscopy and scanning tunnel microscopy make it possible to analyze only the composition of the resulting product. Even though the data reported by the authors of the cited work allowed them to separate the content of clean water from the effects of impurities, the final recommendations of the dosing structure are not given.

An option for overcoming the corresponding difficulties may be the result of study [9]. The cited work describes in detail the methodology for developing an electric drive of a dosing device with the appropriate load and highlights the issue of high-speed PID adjustment. However, the above scheme cannot be widely used in control systems of industrial-technological dosing systems. The multitude of employed structures of control, shut-off piping elements, and systems for coordination of their control, complicates the process of introducing dosing devices and their subsequent adjustment with the help of a controller. That is why the method of partial arrangement of the elements of pipeline fittings lengthwise the entire product pipeline, proposed in [10], is used much more often. However, determining the functional parameterization of a set of stabilizing controllers that ensure the tracking of technological regulations of the dosing process, is a rather complicated process during the introduction of equipment. The use of empirical procedures, proposed by the authors of the cited work, cannot provide for a reasonable calculation of functional mechatronic airlift dosing modules, including changing the characteristics of the liquid flow due to fixation of various operating modes. Issues related to the analytical description of airlift dosing processes remain unresolved, in particular when bringing products through connecting channels and pushing through various cross-sections of nozzles. The issues described allow us to assert that physical modeling [11] helps tackle complex problems of this type. Heuristic tools for modeling control systems, including electro-pneumatic ones, as reported in [12], are combined with more conventional approaches. For example, it is described how statistical analysis helps in solving extremely complex problems of synthesis of the control system with feedback. However, devising such methods for building a technical system with the help of these tools involves both advantages, for example, reducing the time of equipment design, and disadvantages (the time spent on statistical treatment of a large data array).

One example of solving the task of data processing is highlighted in paper [13], which reports the practical and analytical research on devising a methodology for the formal evaluation and design of mechatronic systems; the research results are given in detail. A procedure to design hydraulic mechatronic systems with elements of precision systems has been devised and described, which makes it possible to construct more accurate technical modules with the predefined initial characteristics.

The authors of [14] thoroughly described conditions for synthesizing layouts of the packing machine based on criterion evaluation for individual functional mechatronic modules. Attention is paid to their combination into two main groups of assessments. The results of the performed mathematical-statistical analysis are given regarding the technical and technological characteristics of the main functional modules. However, the applied methods of mathematical calculation of the overall efficiency of OEE equipment do not provide for a complete pattern of the analysis of the accuracy of dosing systems, in contrast to [15]. Numerical and experimental studies of different nozzle positions in the vacuum ejector system were carried out in the cited work. Research into the pneumatic-nozzle control system is supported by modeling results. The cited work's results are useful for justifying the increase in the mass of the product of injection and minimizing energy consumption in the electro-pneumatic system. However, the cited work does not take into consideration the physical and chemical composition of the product.

Regarding the conditions of energy intensity of compressed air control systems, the authors of [16] give the objective function of minimizing energy consumption when filling the rechargeable battery step by step. It is experimentally confirmed that gas compression in the rechargeable battery can be tracked using precision pressure regulators. Note that only one model of the open control system is given; changes in the speed modes of air movement in certain complex sections of the working pipeline are not taken into consideration. In [17], assumptions are stated for the mathematical model of maintaining constant pressure in the flow of working fluid. Only hydraulic circuits of dosing valves operation in the technological flow are given. Based on the conclusions drawn in [18], regarding significant energy losses in dosage systems with elements of pipeline fittings, the area of further research related to airlift precision dosing systems was defined.

Work [19] reports the analysis of flow-type dosing devices where the means of automation is electro pneumatics. The described system is used for portion dosing of drinking water at a temperature from +5 to +90 °C, close in consistency to liquids. However, there are several unattended issues, in particular, energy efficiency and accuracy of the proposed modules. Although the description shows the control systems with feedback, in particular the electronic counter, there is no comparison of theoretical and experimental research results. However, the authors noted a significant acceleration of the dosage operation, provided that pulse valves are used. Paper [20] outlines generalized methodological approaches to the choice of components of pneumatic systems, in particular in dosing mechatronic modules. However, it does not provide a description of the control system. Given the lack of data in [21] on the impact exerted on the dosing process by reliability parameters of technological elements, in particular pneumatic and connecting systems of product pipelines, the results are also not complete.

All this allows us to assert that it is advisable to conduct a study on the synthesis of precision dosing systems of liquid products based on electro-pneumatic complexes. Additionally, by using the empirical research method, the would-be results could supplement the process of forming the dose of the product in the airlift dosing system and the subsequent accuracy of the dosage.

3. The aim and objectives of the study

The purpose of this study is to synthesize the precision dosing system of liquid products based on electro-pneumatic complexes.

This will make it possible to reduce the energy intensity of dosing modules, simplify the design, and facilitate control over the process of forming the exact dose of the product.

To accomplish the aim, the following tasks have been set:

- to devise an analytical description of individual stages of the dosing process, followed by an analysis of individual stages and accepted assumptions;
- to investigate the process of formation and subsequent discharge of the product dose in the dosing receiver and connecting channels and nozzles of the working product pipeline;
- to determine the effect of individual parameters on the accuracy of the formation of the dose of the product, as well as find ways to ensure the necessary distribution of compressed air pressure, subject to compliance with the specified productivity of the dispenser;
- to design an experimental bench for studying the functional mechatronic dosing module under the software-defined modes to form and discharge the dose of the product, based on proportional elements with feedback (4–20 mA).

4. The study materials and methods

4.1. Studying the process of airlift valve-less dosage of liquid products based on electro-pneumatic complexes

Our experimental theoretical studies are based on the use of fundamental laws of the hydrodynamics of liquid media and viscous easily fluid media, the theory of solving ordinary differential equations.

During the research, the static and dynamic characteristics of the control system of the dosing device were taken into consideration; we selected its design parameters aimed at improving the metrological characteristics of the automated dosage system. In order to carry out our experiments, fundamental schemes of universal dosing devices and dosage control algorithms have been developed that ensure the implementation of various laws of the product dose. We also assessed the systematic errors in the proposed portion dosing technique. For the portion systems of automated dosage, based on the principles of airlift system, as well as studies [3, 5, 8, 17], a mathematical model has been proposed to describe the dosing process, as well as the scheme of an experimental installation, shown in Fig. 1. Analysis and synthesis of mathematical models for exact dosage systems are auxiliary in nature; they do not exclude the need for physical modeling and full-scale research. Synthesis involves the mathematical and physical modeling of the airlift dosage of liquid food products.

Additionally, taking into consideration the numerical methods; hydro gas dynamics; authentic technological advances, we performed experimental studies into precision dosage processes of liquid products based on electro-pneumatic complexes.

The diagram of the installation for a valve-free electro-pneumatic dosing device with a control module is shown in Fig. 1.

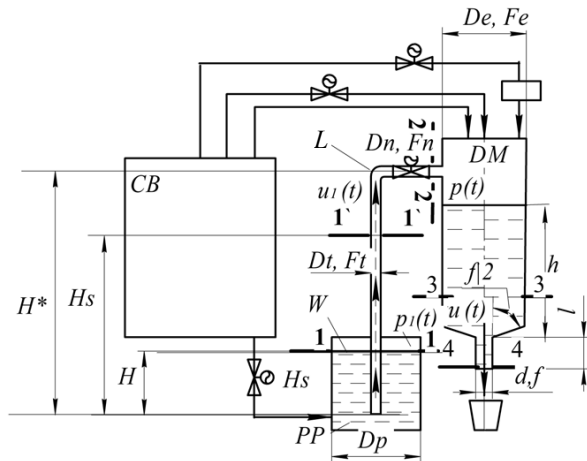


Fig. 1. Scheme of the installation for a valve-free electro-pneumatic dosing device of the airlift type with a control module

Fig. 1 shows the valve-free airlift-type electro-pneumatic dosing device with an additional dosing container that refers to the pressure-type dosing systems. The structure involves a reservoir-feeder (PP) 1 with a liquid level sensor 2 and a system for discharging the product into a dosing receiver (DE) 3. The proposed scheme (Fig. 1) includes a pneumatic control system (KP) 4, which processes pressure signals about PP (p_i) and DE (p) in a programmable logic controller module (PLK) module. Control signals are sent to the dispenser's controlling pneumatic valves 5–8.

PP with a level sensor, DE, and controlling pneumatic valves DU form the object of control OU. The basis of the pressure control system in the dosing receiver is a combination of the control system with feedback (format of the flow loop, 4...20 mA). The possibility of adjusting the control signal, by current, on the solenoid of the distributor of compressed air supply to DU in the range of 0...5 s.

The principle of operation of the dispenser is based on the software control over the pressure supply to the dispensing receiver from PP to the DE mounted above it at height H^*y . It is envisaged to form the dose of the product through the drain nozzle 9 (DE) by changing the pressure in the system of DU with the help of an ejector.

The dosing process is controlled by the amount of pressure p in a closed gas medium of variable volume, which is provided in the process of product discharge.

In the initial state of the dosing module (before dosage), DE through the open valve 7 is connected to channel 10 of the power source. At the same time, the compressed air is blown along the drain nozzle 9, the inlet nozzle 11, and the connecting pipeline 12, which ensures the purity of the product pipeline of the dosing feeder until the beginning of the next dosing cycle.

During the operation of DU under a dosing mode, a command-programmed pressure change is triggered, formed in the control device with PLK.

CAMOZZI elements are used in the experimental bench control system: 130 series drivers proportionally control the AP series valve type distributors (2/2), electronic sensors/pressure switches, SWCN series, the booster pressure stabilizer 40M2L100A120MC02. The pulse-width modulation (PWM) signal, formed by the driver, in a closed circuit of current regulation of 4...20 mA, provides a signal frequency of up to 500 Hz per coil of the solenoid of the elec-

tromagnetic valve supplying compressed air to the dosing receiver and product pipeline system. The supply voltage in the control chain is 24 VDC ($\pm 10\%$), according to the value selected by the AP proportional distributor. The consumption of compressed air would depend on the value of the input main pressure P (0.1...0.3 MPa), and, according to data from [7, 8], is 80...160 (NL/min).

The use of methods of automation of airlift dosing processes is based on a model that could take into consideration the main characteristics of the liquid medium (flow rate, density, pressure, vacuum).

Pressure change control in DU is program-controlled by the pressure regulator (RD) p_1 in the PP and digital vacuum meter. During the operation of RD, the pressure change $p_1(t)$ was formed according to the specified exponential, sinusoidal, law, formed by the help of the signaling program: step-by-step, pulsed, harmonious.

The passing cross-sections of the product pipeline, the nozzle, the output nozzle, as well as the time constant PZ, are selected on the condition that the product discharge in DE exceeds its flow rate through the output cross-section of the nozzle. Accordingly, since the product has been leaked through the outlet cross-section, its level h in DE increases. That also causes an increase in the pressure p of compressed air in DE.

If the p value is achieved, which is equal to the programmed pressure of the dosing feeder p_y , the process of filling DE is completed. PP through valve 5 is connected to the atmosphere, so the pressure p_1 drops to almost zero. At the same time, the blowing valve 7 opens and the excess pressure in DE rises to the value of power pressure. Under the influence of this pressure, the product is discharged from DE through pipeline 12, then the dispenser enters the initial state of blowing.

Under the condition of vacuum forming in DU, a level controller (RU) is triggered, which, in the presence of a deviation of the initial value in PP (parameter H_0) compared to the specified value, forms a control signal for valve 8 to replenish PP. Units RD, PZ, RU are part of the UU composition.

The dosing cycle consists of the stages of filling pipeline 12 with the product, partial filling of DE, and subsequent discharge of the product, subject to the establishment of the UU blowing mode. In the process of DU operation, fixed are the values of structural parameters (passing cross-sections of the product pipeline, nozzle and output cross-sections of the nozzle, height H^* of the DE setup, the length of the pipeline supply of compressed air, and the full volume of DE). Therefore, the time constant PZ and the pressure of power supply 10 the size of the dose volume V_d is the pressure function provided for the dosing feeder p_y and the initial level of filling PP – H_0 . The function $V_d = f_1(p_y)$ is obtained under the condition of an unchanging value of H_0 , which provides the working container characteristics of the dosing module. The function $V_d = f_2(H_0)$ characterizes an error for the fixed values p_y when changing the initial level of PP filling. According to the results of our experimental study, the error value does not exceed 1%, at $H_0 = \text{const}$, and when using two-position pressure regulation $p_1(t)$.

4. 2. Description of an airlift dosing system based on the experimental bench

To assess the impact of various factors on the accuracy of dosing, the following assumptions were adopted. A compari-

son of different implementations of the dosing process during DU operation at a constant amount of pressure programmed for the dosing device p_y was investigated under the conditions of reproducibility of individual stages of the process. The stages of the process were studied in the sequence described above by the algorithm of DU, with the above system of equations of the dosing process.

The stage of filling the connecting pipeline is described by a system that contains two equations for variables $s(t)$ and $H(t)$, where $s(t)$ is the current fluid level in the pipeline, $H(t)$ – the current fluid level in PP.

The free liquid surface motion equation in the connecting pipeline described by the Bernoulli equation for unsteady motion is built for the cross-section 1–1, which coincides with the position of the liquid level in PP, and the cross-section 1'–1', which coincides with the fluid level in the pipeline located at a distance s from the inlet edge of the pipeline:

$$s(d^2s/dt^2) + \frac{\lambda_T}{2D}s(ds/dt)^2 + \frac{1+\xi_T}{2}(ds/dt)^2 + gH_s(s) = \frac{p_1(t)}{\rho} + gH(t). \quad (1)$$

The following designations are adopted: D_T is the diameter of a connecting pipeline; $H_s(s)$ is the height of the cross-section 1'–1' as a function of the parameter s , which depends on the configuration of the connecting product pipeline.

$$p_1(t) \equiv p_{1,3}(t) = P(1 - e^{-t/\tau_0}), \quad (2)$$

$p_1(t)$ is the actual pressure in PP as a function of time t , provided that the programmable RD pressure regulator is perfect; $p_{1,3}(t)$ is the set value of control parameter; $P = \text{const}$ is the power pressure of UU pneumatic elements; τ_0 is the time constant PZ, which depends on the ambient conditions; ρ is the product density; $g = \text{const}$ is the acceleration of gravity; $\xi_T = \text{const}$ is the coefficient of local resistance at the inlet to the product pipeline, which depends on the configuration of the inlet edge of the pipeline; λ_T is the friction coefficient in the pipeline, depending on the Reynolds number $Re_T = \rho D_T(ds/dt)/\mu$, calculated from the Blasius formula:

$$\lambda_T = \frac{0,316}{(Re_T)^{1/4}} = \frac{0,316}{(\rho D_T(ds/dt)/\mu)^{1/4}}, \quad (3)$$

μ is the dynamic viscosity of the product, which depends on temperature.

When constructing equation (1), several assumptions were adopted: coefficients α_{1-1} ; $\alpha_{1'-1'}$ take into consideration the uneven distribution of velocities in the cross-sections 1–1; 1'–1', we accept them equal to 1. In equation (1), we neglect (insignificant values) the coefficient of high-speed pressure of products in PP and take the area of PP cross-sections and the connecting product pipeline as $\Omega = \pi D_p^2/4$; $F_T = \pi D_T^2/4$ is the area of the PP cross-section and the connecting pipeline.

The equation for the balance of fluid consumption with PP is as follows:

$$-\Omega(dH/dt) = F_T(ds/dt). \quad (4)$$

The system of equations (1) and (4) is solved under the initial conditions $s(0) = s_0 = H_0$, $(ds/dt)(0) = (ds/dt)_0 = 0$; $H(0) = H_0$. Solving this system produces the value of function $s(t)$, provided that the time τ_T of filling with the product of the connecting nozzle and the initial speed $u_{1,0}$ of product supply to DE are determined. Once the value of $s(t)$ is known, parameters τ_T , $u_{1,0}$ are determined as:

$$s(\tau_T) = L; u_{1,0} = (ds/dt)|_{t=\tau_T}, \quad (5)$$

L is the length of the pipeline.

The stage of filling the drain nozzle DE necessitates defining the initial conditions for the next stages of the dosing process – product discharge in the outlet cross-section. Given the small size of the nozzle, in particular, its length l and empirical value of the optimal ratio of diameters of the inlet nozzle D_n for DE and nozzle $(d) - D_n/d \geq 1.7$, we accept the condition of exceeding the inflow of the product in DE at each time above the flow rate through the cross-section of the nozzle under the following conditions:

$$\begin{aligned} u_1(0) &= u_{1,0}; H(0) = H_0^* = H_0 - F_T L; p(0) = p_0 \equiv 0; \\ h(0) &= h_0 \equiv 0; v(0) = v_0 \equiv 0; u(0) = u_0 = \sqrt{2gl}; \\ p_1(0) &= p_{1,0} = P(1 - e^{-\tau/\tau_0}), \end{aligned} \quad (6)$$

where $u_1(t)$ is the speed of movement in the product pipeline, $H(t)$ is the current value of the product level in PP; $p(t)$ is the pressure in the gas space of DE during filling; $h(t)$ is the level of the product in DE; $v(t)$ is the volume of the filled part of the DE part without the volume of the drain nozzle; $u(t)$ is the rate of product discharge through the nozzle.

When describing the stages of filling individual DE elements, the initial conditions for the course of the main stages of the process of discharging and forming the dose of the product are defined.

5. Results of studying a precision dosing system of liquid products based on electro-pneumatic control complexes

5.1. Analytical description of individual stages of the dosing process, followed by the analysis of individual stages and accepted assumptions

For the stage of product discharge through the cross-section of the nozzle, an analytical description was built taking into account the pre-formed conditions (6). The equation of motion of the product in the connecting pipeline is represented by the Bernoulli equation for an unsteady motion for the cross-sections 1–1; 2–2, respectively, taking into consideration the condition of equality of diameters of the product pipeline and the inlet pipe DE ($D_T = D_p = D$, $F_T = F_p = F$) that takes the following form:

$$\frac{p_1(t)}{\rho g} + H = \frac{p(t)}{\rho g} + H^* + \left(1 + \xi_T + \lambda_T \frac{L}{D}\right) \frac{u_1^2}{2g} + \frac{L}{g} \frac{du_1}{dt}, \quad (7)$$

$$p_1(t) \equiv p_{1,3}(t) = P(1 - e^{-(t+\tau_T)/\tau_0}), \quad (8)$$

pressure in PP is a function of time t under the condition of the ideality of software pressure regulators RD; λ_T is the friction coefficient in the pipeline, which depends on the

number of Reynolds $Re_T = \rho Du_1 / \mu$, which is calculated from the Blasius formula:

$$\lambda_T = 0,316 / (Re_T)^{1/4} = 0,316 / (\rho Du_1 / \mu)^{1/4}. \tag{9}$$

Similar to equation (1), in equation (7), the α_{1-1} and α_{2-2} coefficients take into consideration the uneven distribution of speed in the cross-sections 1–1 and 2–2. These coefficients are accepted to be constant and equal to 1. Additionally, we neglect the component, equal to $\alpha_{1-1}(F/\Omega)^2(u_1)^2/2$, which takes into consideration the rate of head in PP.

Accordingly, for the cross-sections 3–3 and 4–4, the product flow equation is also built on the Bernoulli equation:

$$\frac{p(t)}{\rho g} + l + h + \frac{\left(\frac{dh}{dt}\right)^2}{2g} = \left(1 + \xi_n + \lambda_n \frac{l}{d}\right) \frac{u^2}{2g} + \frac{l}{g} \frac{du}{dt}, \tag{10}$$

ξ_n is the coefficient of resistance of the inlet of the nozzle, λ_n is the friction coefficient inside the nozzle; α_{3-3} and α_{4-4} are the speed distribution coefficients in these cross-sections equal to 1.

Then, the flow rate balance equation in DE:

$$\frac{dv}{dt} = u_1 F - u \cdot f, \tag{11}$$

$v = v(t)$ is the fluid volume of liquid in DE.

Consider the equation of the gas state in DE:

$$v = V_0 p / (P_a + p), \tag{12}$$

P_a is the atmospheric pressure, V_0 is the DE volume, taking into consideration the volume of connecting channels, except for the drain nozzle. Equation (12) corresponds to the isothermal gas compression in the DE system, provided that the following inequality holds: $P_a \gg p_0 \approx 0$, p_0 is the excess air pressure in DE at moment $t=0$, this is the time of completing the filling the cross-section of the DE drain nozzle with a product.

The equation for the balance of product flow rate in DE takes the following form:

$$-\Omega \left(\frac{dH}{dt}\right) = u_1 F. \tag{13}$$

The equation for the relationship of volume and product level in DE:

$$v = \left(\frac{1}{3}\right) \alpha_1 h_3 + \left(\frac{1}{2}\right) \alpha_2 h^2 + fh \text{ provided } h \leq h_k, \tag{14}$$

$$v = \left(\frac{1}{3}\right) \alpha_1 h_3 + \left(\frac{1}{2}\right) \alpha_2 h^2 + fh \text{ provided } h \leq h_k, \tag{15}$$

accordingly $\alpha_1 = \pi t g^2 \left(\frac{\varphi}{2}\right)$, $\alpha_2 = \pi dt g \left(\frac{\varphi}{2}\right)$, h_k is the height of the lower conical part of DE; $F_e = \pi \frac{D_e^2}{4}$ is the area of the cylindrical cross-section of DE.

Discharging the dose of the product and the subsequent process of switching to the blowing mode using the ejector

occur in accordance with the established algorithm and is achieved by bringing the pressure to the programmed value of p_y .

The process is accompanied by opening valves 5 and 7; at the same time, the pressure in DE increases from the value of p_y to the value equal to the power pressure P . The pressure p_1 in PP decreases from p_{1vd} (the moment of dose cutoff) to zero. Under the influence of pressure P , there is complete drainage of DE. At the end of the process, the pressure p in DE decreases due to the removal of air into the atmosphere through the drain nozzle.

Given the small volume of DE, V_o , and the length of the nozzle, l , its complete drainage occurs significantly earlier than in the combined pipeline, as well as earlier than the pressure p_1 drop to zero in PP.

The drainage of the pipeline occurs under the influence of a positive pressure drop between DE and PP.

Subject to high values of hydraulic resistance of the line, air discharge from PP, and a change in the volume V_{1dv} , which coincides with the time of a dose discharge. The sign of pressure drop between PP and DE may change to the opposite after the drainage of DE.

Then the effect of re-feeding the product to DE and the uncontrolled “additional discharge” of a dose after the completion of the “dosage” stage may occur. The described effect of the “additional discharge” of a dose can be repeated until the compressed air is completely discharged from PP. The conditions described above may cause an additional dosage error. This error is mainly due to two factors:

- possible dissimilarity of the volumes of additional doses, caused, respectively, by different (in separate dosing cycles) values of the volume V_{1dv} of the non-filled part of PP, which is equal to:

$$V_{1dv} = V_{1,0} - V_d, \tag{16}$$

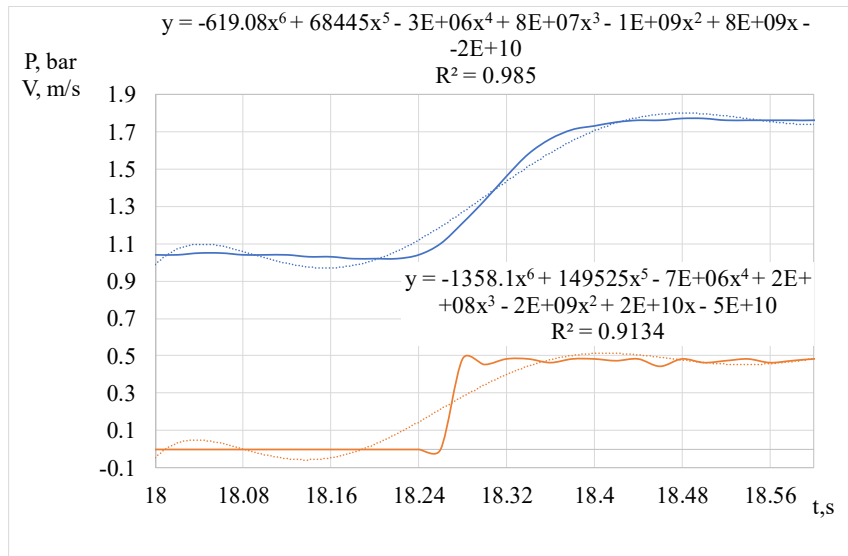
where $V_{1,0}$ is the volume of the non-filled part of PP until the start of the dosing, depending on the value of the initial filling level of PP – H_0 , V_d is the volume of the dosage per one dosing cycle;

- concomitant losses in the pipeline joints.

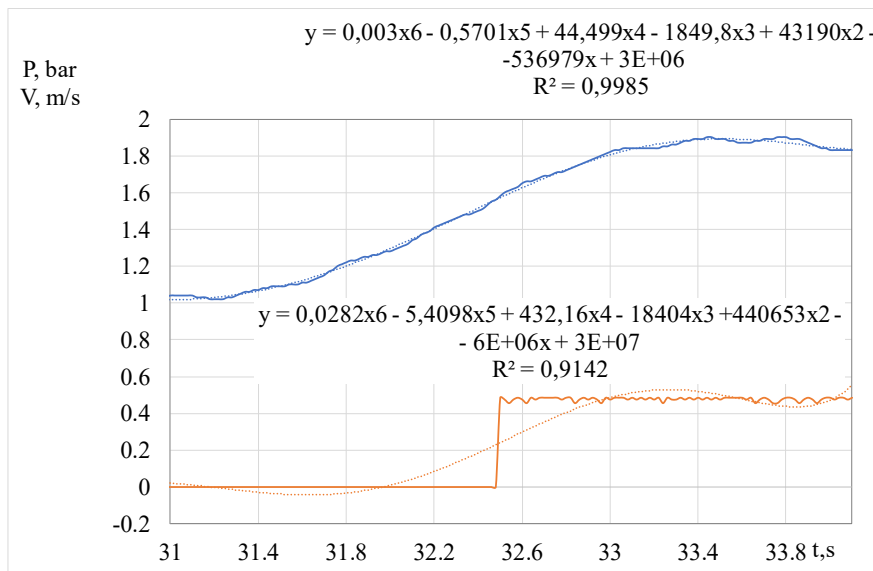
5. 2. The process of forming a dose of the product in the dosing receiver and its connecting channels and nozzles of the product pipeline

Fig. 2 shows the results of our experiment based on the algorithm of change in pressure in the tank of the dosing feeder from excess pressure to vacuum, in accordance with the designed plan of the experiment for dosing drinking water.

The stationary mode is determined by the speed and pressure of the air, which in the process of operation of the installation remain constant, taking into consideration the mode of transportation. Airspeed and pressure at the inlet are the main conditions at the beginning of the stage of selection (discharge) of the dose of the product. The first stage, Fig. 3, *a, b*, demonstrates when the installation enters a stationary mode of product discharge while supplying compressed air to the system within the software-defined pressure change range from 0.99 to 1.81. The pressure change range was chosen by the sorting method, based on tracking a change in the flow rate in the system (0.5 m/s) and the accuracy of the selected dose (50 ml).



a



b

Fig. 2. Characteristics of changes in the main parameters of dosing and pressure control in the system of an airlift functional mechatronic dosing module, in line with: a – step; b – sinusoidal laws; 1 – pressure change, bar; 2 – change in flow rate, m/s

5. 3. Determining the influence of individual parameters on the accuracy of dosage formation for the functional mechatronic module of airlift dosing

The second stage of research, the results of which are shown in Fig. 4, involves the tracking of the working region of changes in the speed of movement of the dosed product in the supply pipeline and the accuracy of dosing. Measurements were carried out using a digital turbine flow meter. The acceleration is due to the time interval of 0.1...0.3 s and depends on the established control modes for the supply of compressed air. Fig. 3, b clearly shows the distribution of the linear displacement rate of the fine-artificial product when moving in the product pipeline channel under pressure. This confirms the modeling results [7] regarding the impact of local resistances on increasing specific pressure losses.

As compressed air accumulates in the feed receiver, the speed and pressure stabilize while the dosage accuracy increases by 2 % (Fig. 4, a, b).

The results of changes in pressure at the inlet and outlet of the product pipeline, shown in Fig. 3, are due to the internal pressure fluctuations of 20 Hz per 1 pressure supply cycle. This mode of air supply is organized by the driver of the 130 series, combined with a network of electric valves for supplying pressure to the system (AR series, Camozzi). At the same time, these dosing modes depend not only on pressure [4, 18] but also on the type of dosed product.

Fig. 4 depicts the characteristics of change in the speed of a product as one of the factors influencing the accuracy of the formation of the dose of the product. The results, shown in Fig. 5, are provided by the limits of the required distribution of compressed air pressure, provided that the specified performance of the dispenser is met.

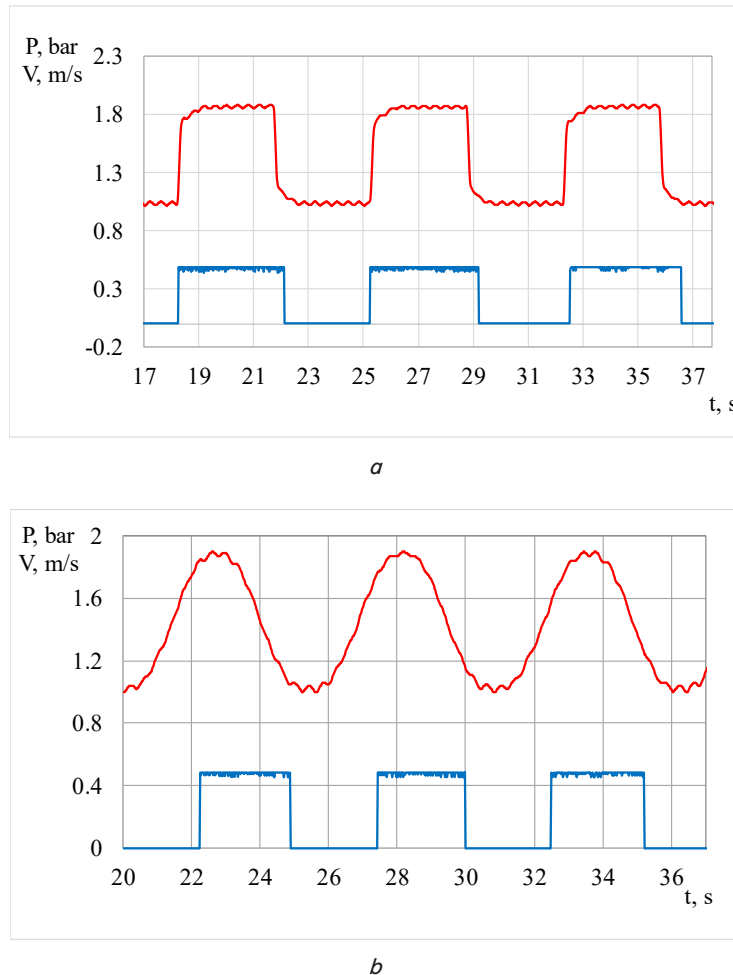


Fig. 3. Characteristics of the laws of control over the parameters of operation of the functional mechatronic module of airlift dosing with changes in pressure in the product pipeline under the following conditions:

- a* – change in pressure and flow rate in the outlet product pipeline under the influence of the control signal according to a step law;
- b* – change in the pressure and flow rate in the outlet product pipeline under the influence of the control signal in line with a sinusoidal law

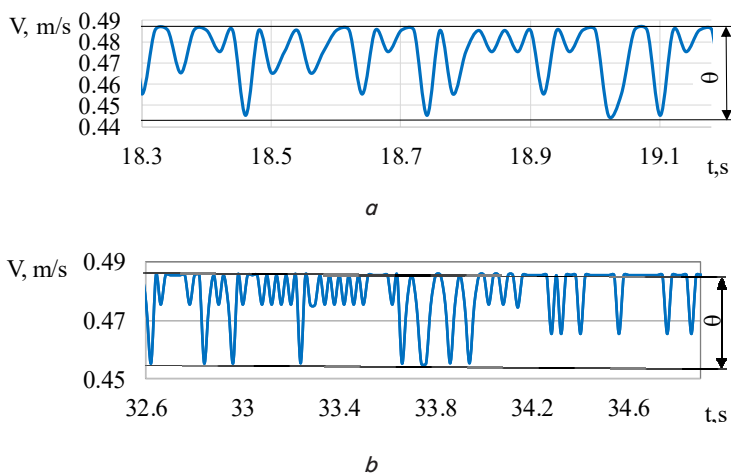


Fig. 4. Generalized characteristic of changes in the speed of movement of the dosed product in the supply pipeline under the following control signal range: *a* – 12.5–17.7 mA, a step law of signal change with a frequency of 7 s; *b* – 12.3–17.7 mA, a sinusoidal signal change law with a frequency of 5.4 s

To determine the initial conditions for further development and research of the airlift dosage module, without dose cutoff valves and elements of pipeline fittings, the product type is taken into consideration.

Thus, in particular, in Fig. 5, an error of dosing accuracy when using a step law of pressure change control in the dosing receiver system is 0.8 % of the set dose of 50 ml. If the step control law is applied, the pressure change in the dosing receiver system is 0.3 %.

5. 4. Experimental bench for studying a functional mechatronic dosing module with the software-established modes of formation and displacement of product dose

To analyze the conditions for ensuring the accuracy of dosing, the structure of an experimental bench of DU was designed (Fig. 5). The flow of the product in the connecting pipeline (from PP to DE) and subsequent movement through the drain nozzle of DU are to be considered as a non-back-

ward one-dimensional turbulent movement of Newtonian liquid. To assess the impact of various factors on the accuracy of dosing, the following assumptions were taken.

The system generates a signal frequency of up to 500 Hz per coil of the solenoid of the electromagnetic valve AP of the supply of compressed air to the system of the vertical channel of the product pipeline.

The supply voltage in the control network is 24VDC ($\pm 10\%$) in accordance with that selected by a proportional distributor.

Compressed air consumption depends on the value of the inlet main pressure P (0.05–0.4 MPa); according to the experimental data, it is in a range of up to 160 (Nl/min).

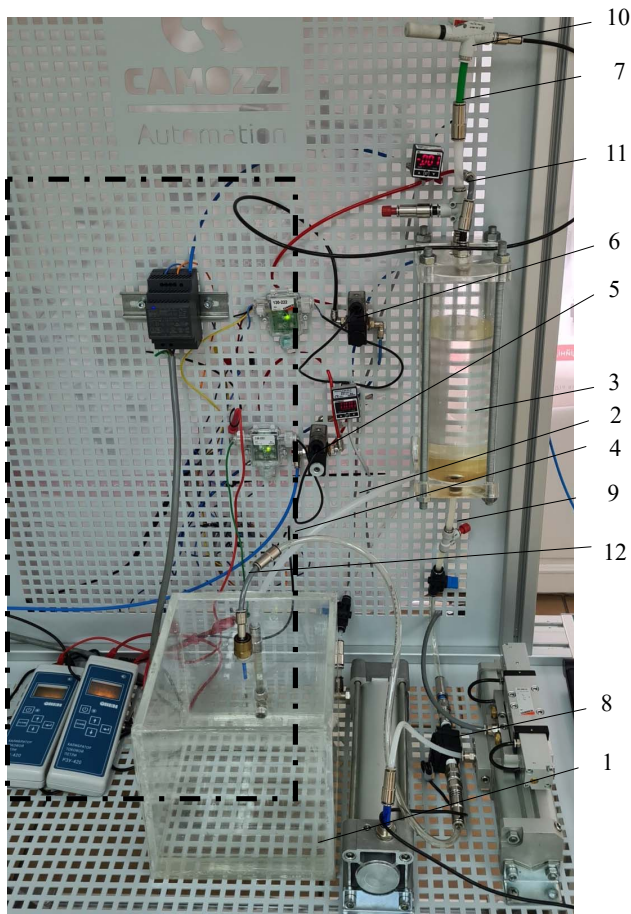


Fig. 5. General view of the experimental bench for studying an airlift dosing system of liquid products: 1 – consumable tank; 2 – level sensor; 3 – dosing capacity; 4 – control system (control drivers for the proportional supply of compressed air pulses; software device setting the law of signal change, 4...20 mA); 5, 6 – proportional direct electromagnetic distributors 2/2; 7, 8 – control pneumatic valves of the dosing feeder; 9 – drain nozzle; 10 – a power supply channel with ejector; 11 – inlet nozzle; 12 – connecting pipeline

The control system diagram, shown in Fig. 6, takes into consideration the possibility of processing liquid food products.

In order to study the functional mechatronic dosage programme, the working modes have been developed and programmed by the system in Fig. 6. The airlift module ensures the formation and discharge of the product dose based on

proportional feedback elements. The series 130 proportional valve control device makes it possible to control any electromagnetic valve at a maximum current of up to 1 A. The standard control inlet signal (0–10 V DC, or 4–20 mA) is transformed into a pulse-width modulation (PWM) signal that makes it possible to send a signal to the electromagnetic valve to form the dose of the product.

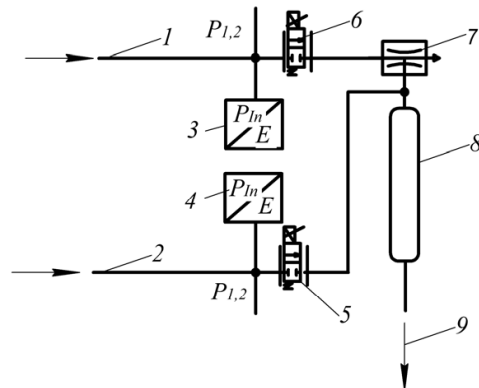


Fig. 6. Generalized scheme of airlift module control at the experimental bench: 1, 2 – compressed air supply pipelines; 3, 4 – pulse-width modulation (PWM) converter; 5, 6 – electro-pneumatic proportional control valves 2/2 NZ; 7 – ejector; 8 – receiver – feeder; 9 – product

6. Discussion of results of the theoretical and physical modeling of the process

The results of change in the pressure at the inlet and outlet of the product pipeline are explained primarily by the fact that the shape of a working channel of the product pipeline and the diametrical cross-section of the working channel to supply and discharge a product from the dosing receiver are taken into consideration. As the dosing process time increases, compressed air is stabilized in the product pipeline; the accuracy of dosing a product is significantly improved. As dosage products, we investigated non-carbonated drinking water (density, 1,000 kg/m³); birch juice (density, 1,000.7 kg/m³), pasteurized milk, 1.5 % fat content (density, 1,025 kg/m³). These parameters are taken for products at 20 °C and 1.013 bars.

The results of changes in the pressure at the inlet and outlet of the product pipeline, shown in Fig. 3–5, are due to the internal pressure fluctuations of 20 Hz per 1 pressure supply cycle. This mode of air supply is organized by the driver of the 130 series, combined with a network of electric valves for supplying pressure to the system (AR series, Camozzi). At the same time, these dosing modes depend not only on pressure [4, 18] but also on the type of dosed product.

Our modeling results make it possible to define the initial parameters for mathematical research to describe the dependences of the main kinematic parameters of the dosage of the product and predict the fall and compensation of head pressure in a dosing system.

Adjusting the time in the control module system using the 130 series driver makes it possible to change the step in the range of 0.1...10 s (Fig. 5). Additionally, precision control systems make it possible to maintain working regulations of the airlift dosing device operation with pressure change modes in line with various laws and conditions. Namely:

$I_{min}...I_{max}=4.1...19.9$ mA; air supply frequency, 0.1...1 Hz;
 $I_{min}...I_{max}=12.3...17.7$ mA; air supply frequency, 0.1...1 Hz;
 $I_{min}...I_{max}=12.5...17.7$ mA; air supply frequency, 0.1...1 Hz.

Our designed experimental bench (Fig. 5) also makes it possible to investigate the accuracy of dosing by using a digital control and measuring complex and change the dose of the product from 20 ml to 750 ml. The choice of dose range was based on providing the manufacturing equipment to small and medium-sized enterprises in the food and pharmaceutical industry.

The limitations of the study results are related to the following parameters: current control value, regarding a standard scale, $I_{max}...I_{min}=4.1...19.9$ mA; the frequency of formation of pulses of compressed air in the product pipeline, 0.1...7 s. Previously, the values of the control signal formed the maximum pressure in the pipe of 0.1...0.5 bar. This confirms the results reported in [20, 22] and predetermines the optimal dosage mode of the product under study.

Features of the proposed method and the results obtained are that the reproducibility of individual stages of the dosing process is achieved. We accept, as mentioned above, the assessment criterion to be the impact of various factors on the accuracy of dosing, it can be achieved provided that the software regulator RD and the driver are perfect.

Additionally, there is an assumption about excluding dosage errors, which are caused by the effect of “additional discharge” of a dose, when the values of working parameters of the functional mechatronic dosing module are constant.

Taking into consideration the conclusions drawn, an increase in the accuracy of dosing can be achieved by complying with the accuracy of the software-assisted regulation of pressure $p_1(t)$ in the PP dosing feeder. The increase is also possible by introducing elements into the structure of the dosing circuit of the product pipeline, which provide automatic compensation for the impact of changes.

The limitation of our study is that it was carried out only for liquid products from the Newtonian media group. The lack of complete experimental data for other types deprived us of the opportunity to perform a more detailed analysis of the effectiveness of the developed structure for a functional mechatronic module of airlift dosing and its calculation methodology. This would be especially relevant for mixing products (suspensions, emulsions) with particles of different diameters (up to 1 mm or larger). The curvature of a working channel in the diametrical cross-section of the product pipeline affects the accuracy of the dosage.

At the same time, the proposed approach makes it possible to derive similar dependences for other dosage modes of these products.

Further research is planned to be carried out to analyze the dosage and packaging processes of other types of liquid products.

7. Conclusions

1. We have analytically described individual stages of the dosing process, followed by the analysis of individual stages and accepted assumptions. When testing an experimental sample of the dispenser, the accuracy of dose repetitions was between 0.35 % and 0.8 %.

The established dose mass was 50 ml ($p=\text{const}$) when changing the initial level of the liquid in PP by 10 mm. That is, in the course of our physical and mathematical modeling, the influence of individual parameters on the accuracy of the formation of the dose of the product was determined; the ways were found to ensure the necessary distribution of compressed air pressure in compliance with the specified productivity of the dispenser.

2. The process of formation and subsequent discharge of the dose of the product (non-carbonated drinking water) in the dosing receiver and its connecting channels and nozzles for the working product pipeline has been investigated. We have built a mathematical model for the dosing process of liquid products. The model includes differential equations for changing the kinematic parameters of the liquid in the dosing channels and the corresponding accepted initial and boundary conditions of the process. The boundary conditions take into consideration the influence of software-established airlift dosing modes using the driver and the geometry of the product pipeline. The measured current value in mA (with an accuracy of 0.001 mA) with respect to the standard scale, I_{min} , $I_{max}=4...20$ mA, was in the ranges of 4.1 mA...19.9 mA; 12.3 mA...17.7 mA; 12.5 mA...17.7 mA. The flow rate characteristics of the pneumatic valve at our experimental bench are in the range of 180 Nl/mn. The duration of the function change period was tracked up to 100 s.

3. The influence of excess and vacuum pressure on the accuracy of the formation of the dose of the product has been established, subject to changes in the ranges of influence: 0.9–1.8 bars; 200–900 mbar. The dose of the product at the time of discharge was in the limits of 50 ml, 100 ml.

4. A structure of the experimental bench was designed, intended to study the functional mechatronic dosing module under the software-defined modes of formation and discharge of the dose of the product. The bench is built on the basis of proportional elements with feedback (4–20 mA), with the help of drivers of the series 130–222 (Camozzi), proportional elements with the feedback system.

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References

1. Yang, A., Pu, J., Wong, C. B., Moore, P. (2009). By-pass valve control to improve energy efficiency of pneumatic drive system. *Control Engineering Practice*, 17 (6), 623–628. doi: <https://doi.org/10.1016/j.conengprac.2008.10.013>
2. Šešljija, D., Čajetinac, S., Blagojević, V., Šulc, J. (2018). Application of pulse width modulation and by-pass valve control for increasing energy efficiency of pneumatic actuator system. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 232 (10), 1314–1324. doi: <https://doi.org/10.1177/0959651818780858>
3. Kanno, T., Hasegawa, T., Miyazaki, T., Yamamoto, N., Haraguchi, D., Kawashima, K. (2018). Development of a Poppet-Type Pneumatic Servo Valve. *Applied Sciences*, 8 (11), 2094. doi: <https://doi.org/10.3390/app8112094>

4. Lengerke, O., Martínez, C. V., Dutra, M. S. et. al. (2008). Mechatronics Design of a Low-Cost Packaging and Dosing Machine for Doughy Products. ABCM Symposium Series in Mechatronics, 3, 717–725. Available at: https://www.researchgate.net/publication/229040784_Mechatronics_Design_of_a_Low-Cost_Packaging_and_Dosing_Machine_for_Doughy_Products
5. Balajka, J., Pavelec, J., Komora, M., Schmid, M., Diebold, U. (2018). Apparatus for dosing liquid water in ultrahigh vacuum. Review of Scientific Instruments, 89 (8), 083906. doi: <https://doi.org/10.1063/1.5046846>
6. Aboulhassan, M. A., Souabi, S., Yaacoubi, A., Baudu, M. (2006). Removal of surfactant from industrial wastewaters by coagulation flocculation process. International Journal of Environmental Science & Technology, 3 (4), 327–332. doi: <https://doi.org/10.1007/bf03325941>
7. Tilahun, M., Beshaw, M. (2020). Customer's Perception and Preference towards Packaged Drinking Water. The Scientific World Journal, 2020, 1–11. doi: <https://doi.org/10.1155/2020/6353928>
8. Lammerink, T. S. J., Elwenspoek, M., Fluitman, J. H. J. (1993). Integrated micro-liquid dosing system. [1993] Proceedings IEEE Micro Electro Mechanical Systems. doi: <https://doi.org/10.1109/memsys.1993.296913>
9. Goubaj, M., Schlegel, M. (2014). Robust PID Control of Electrical Drive with Compliant Load. IFAC Proceedings Volumes, 47 (3), 11781–11786. doi: <https://doi.org/10.3182/20140824-6-za-1003.01006>
10. Lee, K. Y., El-Sharkawi, M. A. (Eds.) (2002). Modern Heuristic Optimization Techniques with Applications to Power Systems. IEEE Power Engineering Society. Available at: http://web.ecs.baylor.edu/faculty/lee/front_rev.pdf
11. Hu, X., Eberhart, R. C., Shi, Y. (2003). Engineering optimization with particle swarm. Proceedings of the 2003 IEEE Swarm Intelligence Symposium. SIS'03 (Cat. No.03EX706), 53–57. doi: <https://doi.org/10.1109/sis.2003.1202247>
12. Behbahani, S. (2007). Practical and analytical studies on the development of formal evaluation and design methodologies for mechatronic systems. University of British Columbia, 164. doi: <https://doi.org/10.14288/1.0080716>
13. Kryvoplias-Volodina, L., Gavva, O., Derenivska, A. (2018). Optimization of the synthesis of packing machines by the efficiency criteria. Scientific Works of National University of Food Technologies, 24 (5), 115–123. doi: <https://doi.org/10.24263/2225-2924-2018-24-5-15>
14. Yang, D., Li, J., Du, C., Jiang, H., Zheng, K. (2015). Injection Performance of a Gas-Solid Injector Based on the Particle Trajectory Model. Advances in Materials Science and Engineering, 2015, 1–8. doi: <https://doi.org/10.1155/2015/871067>
15. Gavva, O., Kryvoplias-Volodina, L., Yakymchuk, M. (2017). Structural-parametric synthesis of hydro-mechanical drive of hoisting and lowering mechanism of package-forming machines. Eastern-European Journal of Enterprise Technologies, 5 (7 (89)), 38–44. doi: <https://doi.org/10.15587/1729-4061.2017.111552>
16. Viall, E. N., Qin Zhang. (2000). Determining the discharge coefficient of a spool valve. Proceedings of the 2000 American Control Conference. ACC (IEEE Cat. No.00CH36334). doi: <https://doi.org/10.1109/acc.2000.879241>
17. Yatsun, S. F. (2008) Dinamicheskie rezhimy dvizheniya klapana pretsizionnogo dozatora zhidkih sred. Izv. vuzov. Seriya: «Mashinostroenie», 8, 37–48. Available at: <https://cyberleninka.ru/article/n/dinamicheskie-rezhimy-dvizheniya-klapana-pretsizionnogo-dozatora-zhidkih-sred>
18. Behbahani, S., de Silva, C. W. (2005). Use of mechatronic design quotient in multi-criteria design, Proceedings of International Symposium on Collaborative Research in Applied Science (ISOCRIAS). Vancouver, 214–221.
19. Borghi, M., Cantore, G., Milani, M., Paoluzzi, R. (1998). Analysis of hydraulic components using computational fluid dynamics models. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 212 (7), 619–629. doi: <https://doi.org/10.1243/0954406981521583>
20. Zhang, T., Wei, C., Feng, C., Ren, Y., Wu, H., Preis, S. (2019). Advances in characteristics analysis, measurement methods and modelling of flow dynamics in airlift reactors. Chemical Engineering and Processing - Process Intensification, 144, 107633. doi: <https://doi.org/10.1016/j.cep.2019.107633>
21. Zhang, H., Liu, M., Wang, B., Wang, X. (2011). Dense gas-particle flow in vertical channel by multi-lattice trajectory model. Science China Technological Sciences, 55 (2), 542–554. doi: <https://doi.org/10.1007/s11431-011-4578-7>