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ARCHITECTURE OF HYBRID MECHATRONIC DOSING AND PACKING MODULE OF PACKAGING MACHINE BASED ON QUALITATIVE ANALYSIS

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A qualitative analysis of the process of packaging liquid products (non-carbonated drinking water) using the example of a hybrid mechatronic dosing and packaging module was performed. The computer model of the mechatronic module is described by the basic operators of the Simulink program, taking into account the differential equations for changing the technological parameters of liquid dosing and the accepted initial and boundary conditions of the process. The modes of operation of the hybrid mechatronic dosing and packaging module are programmed using the driver. The boundary conditions of the process of formation and extrusion of the dose of the product are taken into account. The control system of the module is arranged on the principle of feedback and a sharp change in pressure in the portion receiver (from excess, within 3 bars to rarefaction up to –850 mbar). The analysis of individual stages of the dosing process is described, followed by the elaboration of accepted assumptions. During the tests of the computer model of the hybrid mechatronic dosing and packaging module, the accuracy of repetitions of dose formation was determined within ±0.22 % and 0.9 % of the set value of the dose mass of 50…200 ml.

An experimental bench was designed, which could provide an opportunity to check the results obtained from the computer model. The research results would allow using digital control and measuring equipment to check the accuracy of dosing of the product from 50 ml to 200 ml.

In the course of computer simulation, the effects of the given parameters of the dosing process on the accuracy of the product dose formation were determined, as well as the laws of the necessary distribution of compressed air pressure were formed to maintain the given productivity. The research results could make it possible to improve the designs of liquid product dosing modules and to determine the input parameters for field studies

Keywords: dose formation, hybrid mechatronic module, dosing and packaging operation, feedback, dosing accuracy

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1. Introduction

Given the constant growth in the consumption of packaged food products, the updated requirements of the standards related to the size, shape, type of packaging materials and shelf life are used. The rapid development of packaging equipment creates new urgent tasks, some of which are based on issues of operational efficiency. One of the directions for solving the problems of designing packaging machines of variable productivity is the expansion of the functionality of the basic modules and the introduction of hybrid mechatronic systems at the level of automation.

The design of innovative packaging machines is formed on the synergy of methods of system and matrix analysis, the theory of automatic control, computer simulation methods, and by conducting experimental research.

Hybrid microdosing modules, which are used in the pharmaceutical, chemical, and food industries, are a relevant field of the synthesis of dosing and packaging modules in packaging machines. Current solutions are formed on several types of drives. Most often, electro-pneumo-mechanical mechatronic modules are used. Mathematical and physical modeling of the dosing process for low-viscosity and liquid food products is carried out before the development of the synthesis stages of the control system for further integration into the dosing mechatronic module [1–3].

On the basis of modern software packages, such as Matlab Simulink, models are developed and hybrid control modules with specified parameters of the packaging machine are tested. The informational concept of qualitative analysis combines the tasks of finding parameters of influence on the process of product dose formation and packaging, implementation of simulation models of control of individual functional modules; determination of the optimal values of the operating modes of the packaging machine.

An urgent task during the synthesis of hybrid mechatronic dosing and packaging modules is the study of the control system and software with the condition of monitoring the operation of the mechatronic module based on the principles of "Industry 4.0".

The tasks of designing dosing and packaging equipment are complicated when taking into account various physical and chemical properties of products in combination with the conditions of technical regulations. For example, solving the problem of ensuring high dosing accuracy with the possibility of a wide range of product dose changes. These problems are partially solved in expensive weight dispensers of imported production. However, it should be taken into account that the proposed technical solutions of hybrid dosing and filling modules of packaging machines have a number of fundamental shortcomings that narrow the area for their application [4, 5].

These disadvantages [5–7] include a large number of sensors and mechanical devices, which lead to a significant shortening of the operational reliability of packaging equipment. Features include the increased complexity of control module designs; inconsistency in time of the dynamic parameters of the dosing and packaging process. Another difficulty is the installation of regulating fittings with small diameters of through sections in the product line of the packaging machine. Also, the regulatory narrowness of the current dosing ranges in consumer packaging and the impossibility of quickly converting the packaging machine to dosing products with excellent physicochemical properties are also a drawback. Among the packaging machines for food products, there is a lack of operational readjustment control systems for adjusting technological parameters in the dosing and packaging modules.

Therefore, the task of qualitative analysis of the hybrid mechatronic dosing-packing module of the packaging machine is extremely relevant for the further development of compact, reliable, and inexpensive equipment under the conditions of small-scale production.

Analysis of well-known designs of dosing and filling modules of packaging machines was carried out by many authors who, in order to form physical and mathematical models, significantly simplified the tasks [8, 9]. The results of existing technical solutions for automated dosing and packaging systems are the basis of a large segment of technological lines. However, taking into account the trend of rapid development of "Industry 4.0" and high-precision systems of proportional control of technological flows [10], innovative designs of dispensers require a significant update [11]. The application of qualitative analysis of the hybrid mechatronic dosing and filling module of the packaging machine for liquid and low-viscosity products will form the basis for the synthesis of packaging machines. It is important to provide a range of doses from 0.01 to 20 l and flow parameters from 1 to 1000 l/h.

2. Literature review and problem statement

One of the urgent tasks of designing packaging machines is to provide dosing and packaging modules with universal properties in relation to batch and continuous dosing operations [1]. In the same context, directions for expanding the functionality of dispensers are being explored, while simultaneously maintaining their characteristics in terms of accuracy, reliability, and dosage ranges at a fairly high level [2]. Achieving the set tasks is possible by using a new method of batch dosing based on software regulation of the flow rate of the dosed medium. The issue of introducing into the dosing and packaging modules of packaging machines simple in design sensors that convert the pressure of compressed air into the consumption of the dosed product remains unresolved. After all, modern packaging machines [3], which are equipped with hybrid mechatronic modules, in particular dosing and packaging ones, are equipped with control circuits for two or more technological parameters. Similar control circuits, in which the processes of both continuous and batch dosing are controlled [4], are developed on the basis of typical schemes of hybrid drives with a flow converter. Disadvantages of the standard method of designing dosing and packaging modules and implementing their control system based on the elemental basis of industrial pneumatic automation are the low degree of unification and the introduction of special additional elements. Wide use of pneumatic dosing modules based on pneumatic automation [5] ensures fire and explosion safety of equipment, which is one of the important requirements of most industries. However, there are difficulties in tracking and changing technological dosing parameters in real time in nodes with small cross-sections and the impossibility of quickly readjusting the dose of the product.

Separate works [6, 7] tackle the solution of multicomponent tasks related to dosage. The authors proposed and implemented new schemes for autonomous continuous dosing, mixing, and packaging of products with different components in a given ratio. The solution of such problems requires the use of numerical mathematical methods, which are associated with the presence of iteration cycles, or cumbersome algorithms successfully implemented by computers using modern software. When studying the dosage of multicomponent products, it is advisable to use an object-oriented algorithmic language with a developed graphical interface.

The research results reported in [8] are related to volumetric dosing systems used by packaging machines with relatively stable parameters of dosed products, in particular, density and viscosity. It should be noted that dosing systems with weighing equipment, although more accurate, are complex, expensive, have insufficient speed when dosing liquids and are not sufficiently reliable. The issue of dosage accuracy is also relevant [9]. Closed systems of automatic flow control, with control valves, provide low accuracy at small values of productivity. This is explained by the instability of valve characteristics when working with small pressure drops. The reported results do not have final recommendations for the design of dispensers.

Another disadvantage of weighing mechatronic dosing and packaging modules [10] is the presence of structurally complex standard flowmeters that monitor product supply lines.

Article [11] describes in detail the methodology for developing frequency-pulse control systems for dosing and packaging modules. Such systems contain structurally complex executive units with a large number of hydraulic shut-off fittings, as well as complex mechanical units of control devices.

Quantitative analysis with comparative characteristics of various packaging machines [12] was formed on the basis of simulation of control systems in Simulink. The reported results are combined with more traditional approaches and experimental studies. However, similar methodological approaches to the formation of a technical system do not offer a reduction in equipment development time, and do not highlight the shortcomings of statistical processing of an experimental array of data.

Methods of processing experimental data and forming a qualitative analysis are covered in [13]. A formal assessment of the design of hybrid mechatronic systems with extended research results is described. The proposed methods do not make it possible to design dosing and packaging modules closed by the input parameter.

In work [14], attention is drawn to well-known batch dosing mechatronic modules. By the method of control of the initial parameter, the values of the amount of the dose in the process of its measurement are proposed, with the subsequent control of the moment of the formation of the dose, but without further control of the amount of the dose of the packaged product.

Separate works [6, 7] focus on solving the problems of multicomponent dosing. The authors proposed and implemented new schemes for autonomous continuous dosing, mixing, and packaging of products with different components in a given ratio. Solving such problems requires consideration of the method of simultaneous portion dosing of components of multicomponent products with a given content of components.

The research results reported in [8] are related to volumetric dosing systems used by packaging machines with relatively stable parameters of dosed products, in particular, density and viscosity. It should be noted that dosing systems with weighing equipment, although more accurate, are complex, expensive, have insufficient speed when dosing liquids and are not sufficiently reliable. The issue of dosage accuracy is also relevant [9]. Closed systems of automatic flow control, with control valves, provide low accuracy at small values of productivity. This is explained by the instability of valve characteristics when working with small pressure drops. The reported results do not have final recommendations for the design of dispensers.

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Research [15] is formed by the input parameters of the dosing and packaging module of the packaging machine, which are formed in the signal control device of the productivity task for continuous action, or the dose amount for portioned ones. The results of the work do not take into account the physical and chemical composition of the product.

There are well-known universal dosing modules that are built on the basis of airlift or siphon types unlocked by the output parameter of remote control of continuous action. Implementation of batch dosing operations is ensured by measuring doses over time [16]. The disadvantage of the conclusions is the presence of significant energy losses of the packaging machine as a whole.

The description of the mathematical model for maintaining the constant supplied pressure of the airlift dispenser [17] and the given assumptions substantiate only the pneumohydraulic schemes of the dosing and packaging modules in the technological flow. The conclusions of paper [18] regarding the methods of adjusting the dose by changing the stroke of the piston in the dispenser, the efficiency of readjusting the dose in a wide range of its change, formed further studies. For the composition of the hybrid mechatronic dosing and packaging module of the packaging machine, it is necessary to carry out a qualitative analysis of the main dosing parameters according to the technological regulations. Work [19] considers the analysis of the hybrid drive of the packaging machine, where the means of automation are pneumatics and hydraulics. But there are a number of unexplained issues, in particular the energy efficiency of the described proposals. Work [20] gives generalized approaches to the selection of components of a hybrid electropneumatic dispenser control system. The insufficiency of the description of the layout of the volume-piston type dispenser, the absence of the description of the operational requirements for the proposed design, is the incompleteness of the research. The absence in [21] of input parameters of the simulation modeling model and their influence on the reliability of technological elements confirms the insufficiency of research. The principle of dosing, described in [22], is oriented towards a system with compliance with the condition of constant consumption of the dosing product. The lack of specification regarding the energy consumption of the dosing module leaves a number of unresolved issues regarding the operation of such equipment. The described results of the analysis of existing studies of hybrid mechatronic dosing and packaging modules in packaging machines revealed the need for further development of studies related to ensuring productivity and accuracy of dose formation.

Devising recommendations for setting up mechatronic dosing systems of packaging machines with a high dosing error could ensure the implementation of technological regulations regarding the control over packing liquid products in packages.

3. The aim and objectives of the study

The purpose of this study is to improve the efficiency of the hybrid mechatronic dosing and packaging module of the packaging machine through qualitative analysis based on the principles of physical and mathematical modeling of the process of dosing liquid food products. This will make it possible to expand the operational capabilities of dosing and packaging modules, transform the design and facilitate control of product dose accuracy.

In accordance with the set goal, the following tasks were formulated:

– to design an experimental bench for the formation and subsequent extrusion of product dose packaging in a hybrid mechatronic dosing and packaging module;

– to perform an analytical description of individual stages of the dosing process and accepted assumptions based on the Simulink program of the Matlab software suite;

– to determine the influence of individual parameters on the accuracy of product dose formation, as well as to find ways to ensure the necessary distribution of compressed air pressure, subject to compliance with the specified performance of the dispenser.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is a hybrid mechatronic dosing and packaging module and block mathematical models of its components implemented in the Simulink program using blocks and macroblocks.

Within the framework of this study, the main hypothesis was put forward about the possibility of developing a simplified object-oriented Simulink computer model for a hybrid mechatronic module based on gas dynamics. In order to verify the computer model and identify the influence of the input parameters on the mechanism of formation and subsequent extrusion of the product dose, an experimental bench was designed. During the work on the architecture of the hybrid mechatronic dosing and packaging module, a study of the impact of individual parameters on the accuracy of product dose formation is implied, provided that the specified performance of the dispenser is observed.

During the formation of an analytical description of individual stages of the dosing process, simplifications are adopted, which are most often found in practice in the practice of tasks of continuous and batch dosing. In particular, maintenance of the specified value of the instantaneous flow rate of the dosed liquid; ensuring the measurement of a given dose of liquid within the controlled range of 50...200 ml. Formation of the block structure of the dosing module on closed control systems with controlled readjustment of pressure, time, dose volume, speed of feeding the product into the package. Construction of the architecture of a hybrid mechatronic dosing-packing module with a structure that is low-inertia and universal for batch and continuous dosing operations.

4. 2. Computer simulation of hybrid mechatronic dosing and packaging module

Our theoretical research is based on the principles of the fundamental laws of hydraulics of liquid media, mathematical modeling, and the theory of computer simulation of processes in hybrid mechatronic modules based on gas dynamics. Verification of the mathematical model and detection of the influence of input parameters on the mechanism of formation and subsequent extrusion of the product dose in the model of the mechatronic dosing and packaging module was carried out in the Simulink program. During simulation using Simulink, the principle of visual programming is implemented, according to which the user creates a device model on the screen of the library of standard blocks and performs calculations [11]. The solution of the equations in the Simulink program was based on the methods of solving Normand-Prince differential equations of the 5th order ODE45 with a variable step of integration.

The hybrid mechatronic dosing-packing module was designed for batch systems of automated dosing based on the airlift system, as a result of the improvement of structures in [3, 7, 8, 12]. The proposed mathematical model of the implementation of the dosing process and the block diagram of the computer model of the experimental module based on electropneumatic complexes are given below.

During the simulation of processes of precision dosing of liquid products, the studied product was water and orange juice. The development of a physical-mathematical preliminary model was carried out for preliminary debugging of the work of the future experimental module. For example, to prevent technical calculation errors, as well as to determine optimal control parameters and dosing accuracy.

Underlying the base model is the Matlab R2022b x64 9.13.0.2049777 Mathworks software package. The set of application programs provided a solution to the problem of analytical description of individual stages of the dosing process based on accepted assumptions. The model was formed with the help of Simulink (mathematical library for development and processing of signals) and Simscape (library of elements for physical modeling).

The structure (Fig. 1) of the researched hybrid mechatronic dosing and packaging module for liquid products is given below.

We designed the hybrid mechatronic dosing and packaging module in the form of a computer model and programmed by the system (Fig. 1) to reproduce the operating modes specified by the technological regulations. The airlift component of the module (real object) ensures the formation and displacement of the product dose with the help of proportional elements based on feedback on the pressure and consumption of the product. The electronic part of the control device is programmed and makes it possible to control a given solenoid valve. Initial conditions: maximum current – 1 A; input control signal 4–20 mA, transformation into a PWM signal, supply of control to electromagnetic valves and subsequent formation of the product dose.

Static and dynamic parameters of the module's control system are also taken into account during the research. A block selection was made for further modeling of the technological parameters of the dosing process, aimed at improving the metrological characteristics of the control system. In order to carry out further physical experiments, the schemes of the components of the hybrid mechatronic dosing and packaging modules were developed, and the algorithms for controlling the dose formation process and increasing the accuracy were worked out. The implementation of various laws of pressure change in the control module has been elaborated, for the possibility of changing the dose of the product.

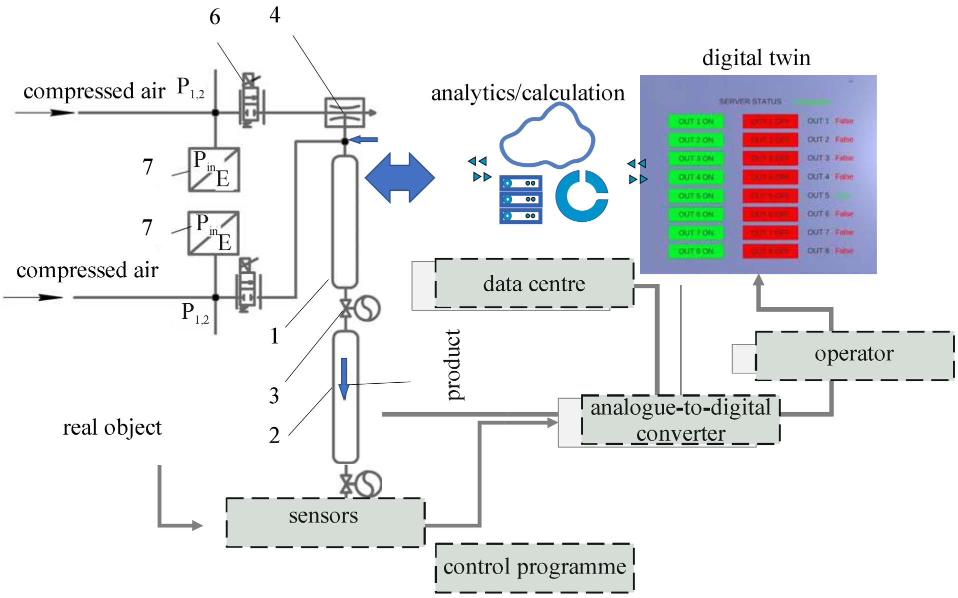

Fig. 1. Structural diagram of the hybrid mechatronic dosing and packaging module for liquid products: 1 – receiver, product feeder; 2 – portion control receiver for dose measurement; 3 – flow meter; 4 – vacuum ejector; 5 – electromagnetic pneumatic valve; 6 – pulse width modulation driver

5. Results of qualitative analysis based on electropneumatic control systems

5. 1. Description of the experimental bench for the formation and subsequent extrusion of the product dose packaging

The general view (Fig. 4) of the investigated hybrid mechatronic dosing and packaging module for liquid products is shown below.

The module shown in Fig. 2 was built on the principle of an airlift type system and valveless electropneumatic dosing devices that belong to pressure type dosing systems. The design is built on the basis of the receiver of the product feeder 1 with the portion control receiver of the dose measurement 2 interconnected turbine-type flow meter 3. The proposed control system of the module works on the principle of a sharp change in the pressure in the receiver 1 from excess (up to 3 bar) to rarefaction to –850 mbar. The rarefaction is provided by ejector 4, which processes pressure signals from the PWM driver 7 and the programmable logic controller (PLC) 8. The supply of control signals, according to the pressure, is provided by the executive electromagnetic pneumatic valves 2/2 5. The current values of the working excess pressure and the rarefaction pressure are correlated by pressure/vacuum sensors 6. TP-Link TL-WR850N is used to ensure communication with remote control panels.

The control system operates on a feedback system (current loop format 4...20 mA) from the pressure/vacuum sensor SWCN-P10-P3-2/ SWCN-V01-P3-2 and the flow meter. Regulation of control signals by current is reproduced by means of a distributor solenoid with a trigger range of 0...5 s.

The process of forming and releasing a dose of the product is controlled by the value of the working pressure p in a closed circuit of a gas medium of variable volume.

The PWM signal generated by the drivers in a closed-circuit regulation with a current of 4...20 mA, at a signal frequency of up to 500 Hz. The supply voltage for control is 24 VDC (±10 %). The consumption of compressed air depends on the value of the input main pressure P (0.1...0.3 MPa), and according to [3, 6], it is within the limits of 80...160 (Nl/min).

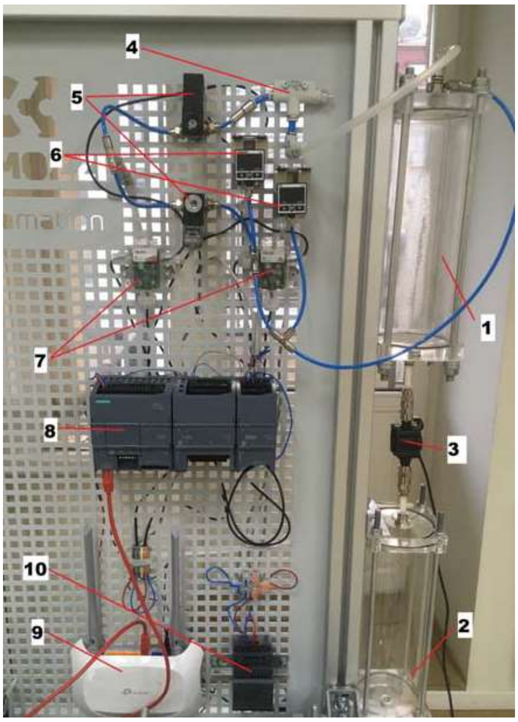

Fig. 2. General view of the experimental bench for the formation and subsequent extrusion of product dose packaging in the hybrid mechatronic dosing and packaging module: 1 – receiver, product feeder; 2 – portion control receiver for dose measurement; 3 – flow meter; 4 – vacuum ejector; 5 – electromagnetic pneumatic valve 2/2 AP-7211-FR3-U711; 6 – pressure/vacuum sensor SWCN-P10-P3-2/ SWCN-V01-P3-2; 7 – PWM signal driver 130-222; 8 – Siemens Simatic S7-1200; 9 – TP-Link TL-WR850N; 10 – MeanWell HDR-60-24 power supply unit

A characteristic feature of airlift dosing research is the formation of a model that takes into account the main characteristics of a liquid product (density, pressure, flow rate, vacuum).

Monitoring of pressure changes in the hybrid mechatronic dosing and packaging module is controlled by software pressure regulators and a digital vacuum gauge. The change in pressure $p_1(t)$ is provided by the specified input signals using the signal application program: half sine wave, sine wave, step wave, triangular wave, sawtooth wave.

The range of pressure change is selected by the screening method, based on tracking the change in the flow rate in the system (up to 0.5 m/s) and the accuracy of the allocated dose (50...200 ml).

5. 2. Architecture of the object-oriented model of individual stages of the dosing process and accepted assumptions based on the Simulink program

During the analysis of the operating conditions of the dosing and packaging module, a schematic diagram was built (Fig. 3). The process of product flow through the connecting pipeline and subsequent movement to the packaging nozzle of the module is considered to be an unsteady one-dimensional turbulent motion of a Newtonian fluid. In order to qualitatively assess the impact of technological factors on dosing accuracy, the following assumptions were made. Research is based on the conditions of reproducibility of individual stages of the dosing process and comparison of different implementations of the process, during the operation of the module, it is conducted at a constant value of pressure, which is programmed for the dispenser p_y. We shall study the stages of the process of forming and allocating a dose according to the sequence described in the algorithm (Fig. 3) with the previously described system of equations of the dosing process [22].

Accordingly, each element of the investigated hybrid mechatronic dosing and packaging module is given a predefined implementation by operators in the Simulink environment:

– "Gas Network" – Reservoir (G) provides the simulation of air in the environment, taking into account parameters: pressure and temperature. The following properties are accepted: $P_a=10^5$ Pa; T_a=293.15 K;

– "Gas properties (G)" forms the definition of gas parameters, in our model: compressed air. Gas constant 287 J/(kg·K); initial compression ratio – 1; temperature of the working environment 300 K; viscosity of compressed air at a pressure of 100 kPa – 18.6 μPa·s; thermal resistance of air layers is 25.88 mW/(m·K);

– "Pressure source (G)" is taken as a source of constant set pressure, representing the entire network pressure supply system (compressor, receiver, booster). Differential pressure 1.5 bar; the diameter of the inlet and outlet pipelines is 6 mm;

– "2-way directional valve (G)" forms the operation of a normally closed 2/2 valve, where A is an input, B is an output, S is a control signal input. Valve switching time 20 ms; conditional passage of the flow cross-section 2.4 mm; coefficient of consumption of the working medium (compressed air) k_v=1.7 l/min; maximum working pressure up to 4 bars; maximum consumption 113 Nl/min;

– "Pipe (G)" provides the simulation of gas movement through the pipeline with corresponding losses and temperature exchange, where A is input, H is temperature influence, B is output. The length of the pipeline is 0.1 m; pipeline diameter 6 mm; Re_1=2000, Re_2=4000, Nu=3.66;

– "Tank (G-TL)" simulates a hermetic capacity (receiver) with gas and liquid (DM) and connects the network of the object with gas and liquid from the outside. $A1$, $B1$ provide inputs for the gas network, $A2$ is an input for the liquid network, $H1$ – thermal effect on the gas (air), $H2$ – thermal effect on the liquid (product), V – volume of liquid in the tank (receiver), L is the liquid level in the receiver;

– "Thermal liquid settings (TL)" represents the properties of the liquid (drinking water);

– "Check valve (TL)" simulates a non-return valve, provides an open section of the nozzle in the model;

– "Interface (TL-IL)" is an element for transferring fluid parameters from a thermal fluid network to an isothermal fluid network;

– "Isothermal liquid properties (IL)" represents the properties of a liquid (drinking water);

– "Pipe (IL)" simulates the movement of liquid (drinking water) along the pipeline with corresponding losses (A – input, B – output);

– "Tank (IL)" represents the receiving capacity (receiver) under atmospheric pressure, where A is the liquid input, V is the value of the liquid volume in the container, L is the value of the liquid level in the container;

– "Temperature source" forms the thermal influence of the environment at room temperature;

– "Solver Configuration" is a block of configuration of the method for solving the equation;

– "PWM Generator (mask) (link)" provides a PWM signal generator in the model, based on an analog control signal.

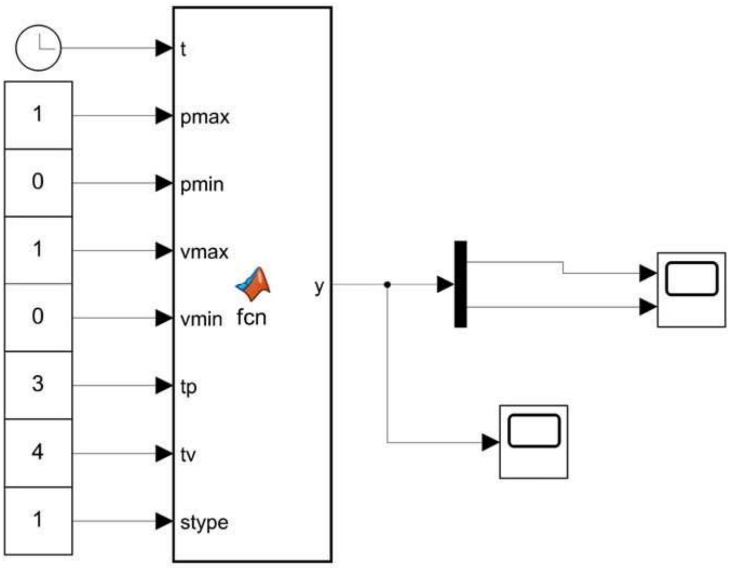

Fig. 3. Generating subsystem for the module control signal: pmax – the maximum set level of control pressure at the input (0–1); pmin – the minimum control pressure level at the input (0–1); vmax – maximum vacuum level (0–1); vmin – minimum vacuum level (0–1); tp – pressure exposure time; tv – vacuum exposure time; stype – specified type of signal (0 – half wave according to sine wave, 1 – wave according to sine wave, 2 – step function, 3 – triangular wave, 4 – sawtooth wave)

The control algorithm of the hybrid mechatronic dosing and packaging module combined a model of a programmable logic controller (PLC) and a personal programmer into a common unit. In general, this element is a parametric signal generator (Fig. 2). The proposed system is built in MATLAB Function, for signal processing in the Simulink environment based on the code.

For the formation of the observational function of qualitative analysis, the elements of the library of control and measuring devices were selected:

– "Pressure Sensor" – pressure measurement (where input *A* is the measured pressure, input *B* is the reference pressure value (atmospheric pressure), *P* is the working pressure value);

– "Volume Sensor" – measurement of volume consumption of the product (where *A* is the input, *B*, *V* – the output, which records the value of the consumption).

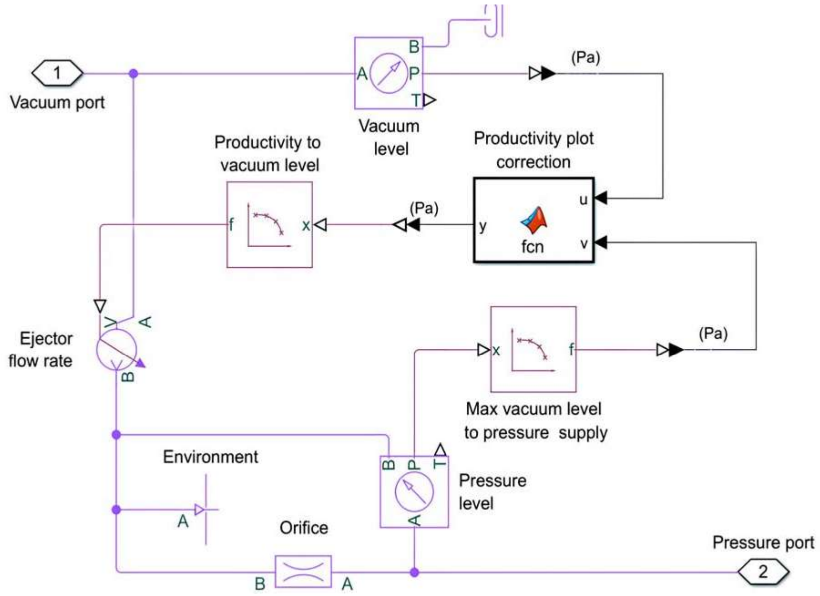

Fig. 4. Block diagram of a computer model of a mechatronic vacuum ejector

To ensure the real components of the schematic diagram (Fig. 1), a separate model of a vacuum ejector was developed, the prototype of which is the VEBL-10H-T2 – Camozzi device. The formed computer model of the vacuum ejector is shown in Fig. 4. The model is identified with a pressure sensor (Pressure level), which is installed in front of the nozzle, and depending on the value of the working pressure at the inlet P=2...6 bar, a vacuum depth at the outlet P_v=–350...–850 mbar is formed in the ejector. To validate the simulation results, the comparison of the dependence of the vacuum depth on the vacuuming time was changed.

The model of the mechatronic vacuum ejector ensures the adjustment of productivity, that is, air consumption, depending on the depth of the vacuum. Within the limits of the model, the maximum productivity of the ejector in terms of air consumption is F=50 l/min.

According to the results of the selection of the components of the computer model of the hybrid mechatronic dosing-packaging module, technical parameters were set that make it possible to reproduce real research objects. The physico-mathematical model of the studied module is shown in Fig. 5 with the possibility of influencing the regulation of the dosing operation.

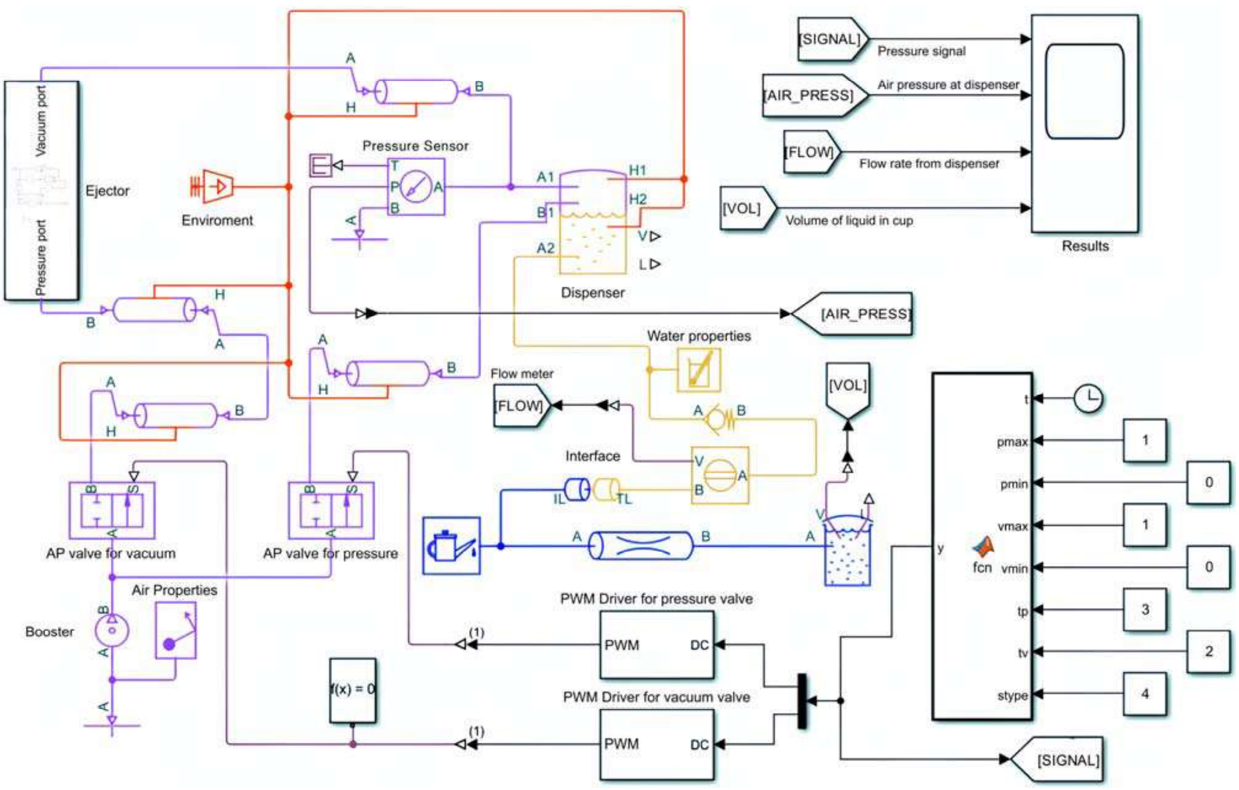

Fig. 5. Computer model of hybrid mechatronic dosing and filling module implemented by Matlab Simulink

Taking into account the need for further field tests of the module, in which there are complex objects, during the simulation of the dosing process, frequency methods for the analysis of dynamic characteristics were not used. Attention was focused on methods of system research and calculations in time domains. Transient processes caused by stepped, harmonic, or impulse effects in the systems were determined.

5. 3. The influence of individual parameters on the accuracy of product dose formation

The next stage of research, the results of which are shown in Fig. 6, are related to tracking the work area to change the parameters of the work environment.

The research was carried out into pressure, pressure in the middle of the dosing and packaging module, the speed of movement of the dosed product to the packaging nozzle and the accuracy of the formed dose in consumer packaging. Measurements were carried out using a computer model (Fig. 5) during different types of control signal (Fig. 6). Namely, a sinusoidal half-wave (Fig. 6, *a*), a sinusoidal wave (Fig. 6, *b*), a stepped wave (Fig. 6, *c*), a triangular wave (Fig. 6, *d*), a sawtooth wave (Fig. 6, *e*).

Modeling was carried out under the following conditions. Pressure signal (maximum working pressure) – from 3 to 6 bars.

Air Pressure at dispenser (pressure in dispenser up to 1 to 3 bar). Flow Rate from dispenser (product speed during packaging within $0.3\cdot10^{-3}$ m^3/s). Volume of liguid in cup (fixed dosing volume from 50 to 200 m^3). Velocity and pressure, during the operation of the dosing model, maintain stable values throughout the simulation under the influence of input action on the sinusoidal half-wave and dust wave. Dosing accuracy is fixed within 0.92 %. During the tests of the computer model of the hybrid mechatronic dosing and packaging module, the accuracy of repetitions of dose formation was determined within ±0.22 % and 0.9 % of the set value of the dose mass of 50...200 ml.

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

Our results of computer simulation (Figs. 3–5) are justified by the fact that the computer model takes into account the performance characteristics of real equipment elements and the shape of the working channel of the product pipeline and the diametrical section of the working channel for the input and extrusion of the product from the dosing receiver. If the time of the dosing process increases, stabilization of the energy carrier (compressed air) is observed in the product pipeline, which ensures an increase in the accuracy of the product dose.

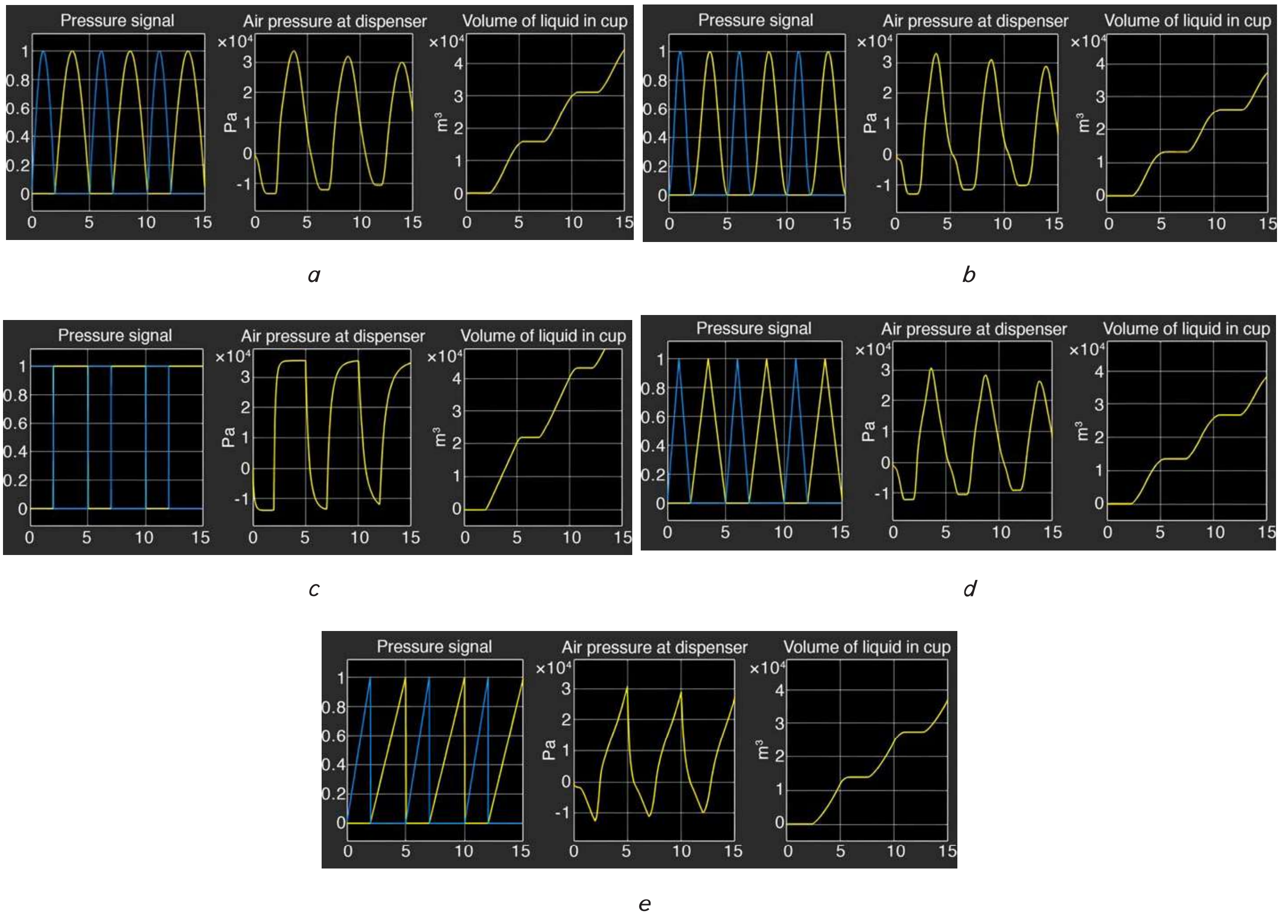

Fig. 6. Computer simulation of reactions of the hybrid mechatronic dosing-packaging module to different types of input influence: *a* — half-wave sinusoidal; *b* — sinusoidal wave; *c* — step wave; *d* — triangular wave; *e* — sawtooth wave

In particular, in Fig. 3, an observation function of qualitative analysis is formed from the elements of the library of control and measuring devices, which provides verification of the setting of real components for the schematic diagram of the experimental bench. Controlling the change in pressure in the hybrid mechatronic dosing and packaging module is controlled by software on the block diagram (Fig. 4), the computer model of the mechatronic vacuum ejector according to the air flow and is F=50 l/min.

The physico-mathematical model of the studied module is shown in Fig. 5, it provides a current influence on the adjustment of the dose volume and accuracy during the dosing operation. The blocky nature of the computer model makes it possible to study the dynamics of filling and emptying of the dosing chamber within the limits of the change of control influences over time (0.5…15 s).

Shown in Fig. 6, the results of changes in liquid flow rate, pressure at the inlet and outlet of the product line are formed under the influence of internal pressure fluctuations up to 20…40 Hz for 1 cycle of pressure supply. The specified operating mode of air supply is provided by a PWM driver connected to a network of pressure supply solenoid valves in the product line system. We note that the specified dosing regimens depend not only on pressure [2, 3, 22] but also on the type of dosed product, in particular, its physical and mechanical characteristics.

Setting the timer in the module control system according to the driver's characteristics made it possible to change the time within 0.1…15 s (Fig. 5). Also, the settings of the computer model control system support the operating technological regulations of the hybrid mechatronic dosing and packaging module. The studied modes of pressure change with different laws and assumptions: current load Imin…Imax=4…20 mA, air supply frequency 0.1…1 Hz.

The manufactured design of the experimental bench will provide an opportunity to check the obtained results of the formed computer model. With the help of digital control and measuring equipment, we check the accuracy of dosing of the product from 50 ml to 200 ml. The choice of the dose range is justified by provision for the food and pharmaceutical industry (packaging of medicines, nutritional supplements).

At the same time, the proposed approach allows obtaining similar dependences for other dosing regimes of the specified products.

Further research is planned to analyze the dosing and packaging processes of other types of liquid products.

The limitations inherent in this study are related to the control of energy transfer and ensuring greater stability in the product pipeline network and product supply from the feeder to the dosing receiver. In particular, the transient process with a stepwise change in the input signal is limited to the formation of a dose of up to 200 ml, a change in the pressure control signal to 4 bars. Energy consumption is related to the suction of the ejector model, which is identified with the pressure sensor. Pressure level is set in front of the nozzle and depending on the value of the working pressure at the inlet P=2…6 bar, a vacuum is formed in the ejector at the outlet P_v=–350…–850 mbar.

The shortcomings of this study can be noted in the simplifications for modeling, which are implemented in Matlab Simulink and are related to one type of product (drinking still water). In the future, they can be eliminated using the results of experimental studies on the proposed bench.

7. Conclusions

1. An experimental bench has been designed for researching the processes of formation and subsequent extrusion (packing) of a product dose in a hybrid mechatronic dosing-packing module. The bench is designed on the principle of an airlift type system and valveless electro-pneumatic dosing devices, which belong to pressure-type dosing systems. The structure includes a product feeder receiver with a portion control receiver for dose measurement, which are connected to each other by flow meters. The proposed bench control system works on the principle of a sudden change in pressure in receiver 1 from excess (up to 3 bar) to rarefaction to –850 mbar. Rarefaction is provided by ejector 4, which processes pressure signals from the PWM driver. The experimental bench makes it possible to physically simulate the stages of research on the reactions of the hybrid mechatronic dosing and packaging module to various types of input influences.

2. Analytical studies were carried out with a description of individual stages of the dosing process and accepted assumptions, formed in the Simulink program of the Matlab software suite. A computer model of the operation of the hybrid mechatronic dosing and packaging module for the dosing process of liquid products - drinking water – has been developed. The model is formed on the differential equations of changes in the kinematic parameters of the liquid in the sections of the dispenser with the corresponding accepted initial and boundary conditions of the process. Boundary conditions are formed taking into account the effects of software-set modes during dosing according to the airlift principle, using the driver and the geometry of the product line reproduced in the model. The value of the current during simulation was formed in mA (accuracy, 0.001 mA) to the standard scale Imin, Imax=4…20 mA.

3. The effects of individual parameters on the accuracy of product dose formation during the specified dosing regimes were determined. We formed ways to ensure the necessary distribution of compressed air pressure, subject to compliance with the specified performance of the dispenser. We built the graphs of changes in the main technological parameters of the module, formed on the principle of separate stages of the dosing process. It was determined that the computer model has the same characteristics of changes in the main parameters of the dosing process (pressure, speed, product consumption and energy carrier) – without obvious jumps. In particular, the characteristics of product consumption indicate the uniformity of dose formation.

Pressure signal (maximum working pressure), from 3 to 6 bar; Air Pressure at dispenser (pressure in dispenser up to 1 to 3 bar); Flow Rate from dispenser (product speed during packaging within $0.3 \cdot 10^{-3}$ m^3/s); Volume of liguid in cup (fixed dosing volume from 50 to 200 m^3). Velocity and pressure, during the operation of the dosing model, maintain stable values throughout the simulation under the influence of input action on the sinusoidal half-wave and dust wave. During the tests of the computer model of the hybrid mechatronic dosing and packaging module, the accuracy of repetitions of dose formation was determined within ±0.22 % and 0.9 % of the set value of the dose mass of 50...200 ml.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

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