Simulation of hydrodynamic phenomena in valve feeders of adaptronic modules for dosing liquid products

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Abstract

Introduction. Rational geometric and hydrodynamic parameters of valve feeders of adaptron modules for dosing liquid food products in automatic packaging machines are determined.

Materials and methods. The study of hydrodynamic phenomena based on the simulation modeling of the feeder operation with liquid media, the physical and mechanical characteristics of which are close to Newtonian liquids, was conducted. A feeder with a conical valve and purified drinking water were used in the study. The feeder throughput was 500 cm^3/s; the internal diameter of the drain nozzle was 20 mm.

Results and discussion. To ensure the continuous flow, minimum overall dimensions of the feeder, and the possibility of regulation by changing the throughput of the feeder nozzle according to a given law, the angle at the base of the cone should be within 50–60°, and the length of the saddle base 20–25 mm.

During the movement of the liquid in the valve feeder, three negative factors affecting the parallel laminar movement of the liquid were found: (a)reverse movement of the liquid when it comes into contact with the surface of the base of the valve cone; (b) turbulence cells at the entrance of the liquid into the valve channel, and (c) the tubular form of the liquid flow in the nozzle. These negative factors can be eliminated by using a ball-conical valve with a truncated top.

To eliminate turbulence cells in the valve feeder, counter-current movement of liquid, and tubular flow of liquid in the nozzle, it was proposed to make the valve in the form of a conical-spherical shape with a cut-off cone top, and also to extend the inner surface of the seat to the inner surface of the measuring cylinder of the feeder.

Under such conditions, a parallel flow of liquid is ensured, which contributes to the accuracy of dose formation and the duration of product storage.

Conclusions. The design of the valve in the form of a conically spherical figure with a cut-off cone top according to the provided recommendations allows eliminating the centers of turbulence in the movement of liquid products in the valve feeder.

Introduction

Automatic machines for packaging of food products in consumer packages are characterized by a large number of indicators of technical excellence, which determine their competitiveness. One of these indicators is functional accuracy (Gavva et al., 2023). In machines in which dose formation is provided before packaging, the indicators of functional accuracy are the accuracy of product dose formation._According to international standards, the tolerance field for dosing accuracy is in the plus field. It is possible to ensure such requirements and taking into account the efficiency of the machine by developing and implementing the latest technological systems based on elements of mechatronics, adaptronics, micro-drives, and micro-sensors.

In the presence of modern computer technologies for managing technological processes, technical means, the best results can be achieved by applying the product weighing method. For products characterized as a solid medium, dynamic weighing is typical (Gavva et al., 2023). Dynamic weighing is affected by a significant number of factors that can be taken into account when implementing adaptronic modules.

The implementation of adaptronic modules for dosing of liquid products in a weighted way involves establishing functional dependencies between the flow of products through the feeder nozzle and the structural and kinematic parameters of the valve, which changes the amount of product flow. Therefore, the search for rational parameters of adaptronic dosing modules is an urgent task that requires modeling and research of hydrodynamic phenomena in feeders, which, for the most part, are based on the application of product flow separation valves.

The formation of a dose of a light-flowing bulk product, which in terms of structural and mechanical properties is close to a Newtonian liquid, was investigated by weight method (Badiru et al., 2023). The dynamic component of the weighing force is significantly affected by the mode of product power flow. In order to optimize the dosing and packaging operation in terms of its duration and accuracy of dose formation, it is important to ensure the appropriate law of changing the throughput of the feeder (Rangappa et al., 2020). This task can be solved in different ways: by using valve system, pneumatic, shut-off valves (Bauer, 2019; Gavva et al., 2023).

In functional modules with a valveless power supply system, it is quite difficult to implement the required product flow modes. Each type of liquid products has certain properties that have a corresponding effect on the geometry of the feeder and the pressure control system (Ma, 2017)._Existing packaging machine designs widely use a valve system with an individual actuator on the valve and a microprocessor control system for valve movement relative to the nozzle seat (Brody, 2000). The effectiveness of controlling valve movement depends on its geometric shape and nozzle seat (Gavva et al., 2023).

It was established that the cone valve makes it possible to most effectively implement the law of its movement and change the throughput of the feeder.

Much attention is paid to the modeling of hydrodynamic phenomena in dispenser feeders (Petrenko, 2021). Thus, electrical methods are still widely used today (Vazguez-Santacruz, 2023), but they cannot ensure the completeness of the feeder calculation, including the change in flow characteristics under different operating modes (da Silva, 2019; Lammerink, 1993). The accuracy of product dosing is considered in works (Vavrik et al, 2023; Furmann, 2017), where the authors confirm that dosing systems with weighing equipment are more accurate and reliable.

Hydrodynamic phenomena in faucets, valve feeders are also investigated using computational fluid dynamics (CFD) (Zic et al, 2020). Computational hydrodynamics is used to obtain important information based on the analysis of liquid flow in faucets and feeders through simulation modeling.

Thus, with the help of the ANSYS program (Jia et al., 2021), four different shapes of the V-sector valve core hole were studied. In the work (Song et al., 2009), the authors used the finite element method to study the design of ball valves in order to optimize mass and dimensions. The particle flow tracking method (PTFV) is also used for research._The phenomena that occur during the closing and opening of ball valves were investigated in work. (Cui et al., 2017). The obtained results can contribute to increasing the productivity of cranes by stabilizing the dynamics of the liquid flow. Experimental studies of throttle valves (Dumitrache et al., 2018) made it possible to compare the effectiveness of their functions.

The results of experimental studies of ball valves at different volume opening angles are given in work (Chernet al., 2007). The analysis of research results showed the impossibility of smoothly regulating the fluid flow with ball valves.

Takase et al (2022) considered the tasks of multi-component dosing of liquids. To solve such problems, it is necessary to consider the method of simultaneous portioned dosing of components of multicomponent products with a given content of components._The results of these studies are not aimed at the formation of a flow of liquid products of a given capacity, and they also do not have final recommendations regarding the design of the feeder, methods of regulating product flows. The analysis of the results of the performed studies confirmed their imperfection for the creation of the latest samples of adaptronic modules for dosing liquid products by weight method.

The aim of study is simulation modeling of hydrodynamic phenomena and substantiation of rational values of geometric and kinematic parameters of the feeder of the adaptronic dosing module with a conical valve for dividing the flow of liquid products.

The tasks of the research are:

- to develop a simulation model of fluid movement in the intervalve channel of the feeder with a variable value of the angle β at the base of the valve cone and to evaluate characteristic changes in hydrodynamic parameters;
- to develop a simulation model of fluid movement in the intervalve channel of the feeder with a variable base of the base l_0 of the saddle of the feeder nozzle and evaluate characteristic changes in hydrodynamic parameters;
- to develop a simulation model of fluid movement in the intervalve channel of the feeder at different surfaces of the cone valve base and evaluate characteristic changes in hydrodynamic parameters;
- check the adequacy of simulation models of fluid movement in the intervalve channels of the feeder with a real process.

Materials and methods

Adaptronic module for dosing liquid products by weight method

Adaptronic modules of different structure and composition are used to implement the weighing method of dosing liquid products._Figure 1 shows the improved structural diagram of the adaptronic dosing module, which provides for control of the current values of product weight, the flow rate of products in the feeder, and the level of products in the container.

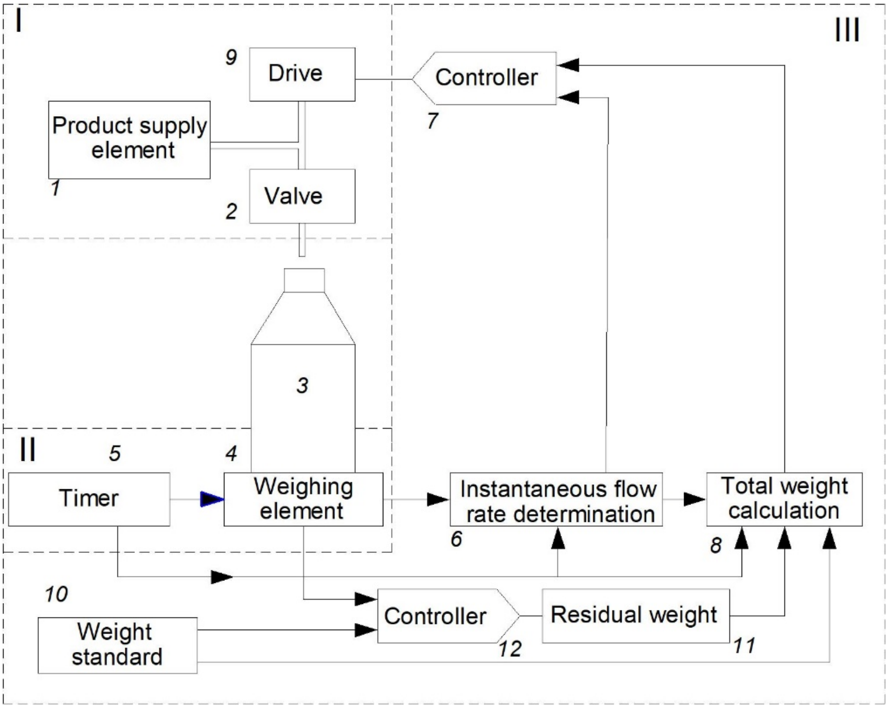


Figure 1. Structural diagram of the adaptronic module for dosing liquid products by weight method

According to this scheme, the product enters through the supply element 1, which is connected to the valve 2 and the device 6 for equalizing the instantaneous flow rate of the liquid in the feeder. For the most part, the change in the capacity of the feeder is provided by the vertical movement of the valve._The valve movement gradient is realized by sensor drives (pneumatic, electric). To ensure laminar modes of fluid movement in the valve channels of the feeder, at the moment of valve opening and closing, a pneumatic product pressure regulator is installed in the product supply element._A consumer packaging 3 is located under the nozzle of the feeder with valve 2. Consumer packaging 3 is installed on the platform of the weighing element 4. The adaptronic module also includes a timer 5, which provides a common temporal reference base for all elements of the structure that implement the process of product formation and dosing.

For full control of product dosing, the weighing element 4 is connected to the device 6 for measuring the instantaneous rate of product flow in the feeder, and this device is connected to the control element 7 and the element for calculating the total weight of products and consumer packaging 8. To measure the values of instantaneous product consumption, the signal from weighing element 4 is received at regular time intervals._The obtained instantaneous value of the product flow rate is first transmitted to the control element 7, which forms a command for the position of the valve 2 relative to the nozzle seat, and then to the element for calculating the total weight 8 (product in the consumer packaging).

The control element 7 of the valve position 2 also receives the value of the product flow rate 9, with which the measured flow rates are compared to adjust the position of the valve 2. Along with this, the product total weight calculation element 8 receives the signal from the weight element 10 and the added product weight determination signal 11. The total weight calculation element 8 compares the calculated total product net weight with the indicators of the signals 10 and 11 and forms the signal of the element 7 to reduce or stop the product flow when the two values are the same.

The weighing element 8 signals to the element 12 to calculate the average rate of consumption of the product stream, after which the resulting signal is transmitted to the comparator 13, which also receives signal about the relative average rate of consumption of the product stream 14. The real weight of the products in the consumer packaging (net) is calculated by subtracting the weight of the consumer packaging from the total weight (gross). The signal corresponding to the net weight of the products is sent to the comparator 15, which compares the real weight of the products with the reference value 10.

Determining of weighing process components

The weighing process includes the static component P_{st} – the weight of the consumer packaging and the dynamic component P_d – the movement of products into the consumer packaging:

$$P=P_{st}+P_d$$

The static component of weighing is fixed before the product is packaged. Assuming that the amount of deformation of the tension beam of the weighing system is very small, the dynamic component of the movement of the container during product filling is less than the error of the measuring elements.

The dynamic component of weighing for liquid products with a small value of dynamic viscosity can be represented by a combination of two elements. The first element is the weight of products moved into the container during time t. The second element is the load perceived by the weighing system from the flow of products.

$$P_d = \rho \cdot Q_f \cdot t_i \cdot g + \rho \cdot Q_f \left(\vartheta_2 + \varepsilon \sqrt{2g \left(h + \frac{\Delta P}{\rho \cdot g} \right)} \right),$$

where Q_f is the throughput capacity of the feeder nozzle is determined $Q_f = f_{ef} \cdot \vartheta_2$;

f_{ef} – effective cross-sectional area of the flow of products moving from the nozzle;

ϑ_2 _the average speed of movement of the flow of products from the nozzle;

ρ – volumetric mass of products;

G – gravitational acceleration;

ε – coefficient of aerodynamic resistance of moving products into the consumer packaging, usually accepted $\varepsilon=1$;

H – the height of the liquid flow from the end of the nozzle to the liquid level in the consumer packaging. This value is variable depending on the state of filling the consumer packaging;

$\Delta P=P_1-P_2$ – pressure difference inside of consumer packaging and in the environment.

Construction of feeder of adaptronic dosing module. Data for modelling

The main factors affecting the accuracy of product dose formation by other weighing methods are the parameters of the element of dynamic component weighing and the speed of the shut-off valve.

To manipulate the influence of the second element of the dynamic component of weighing on the accuracy of dose formation while ensuring the specified performance of the adaptronic module, it is necessary, with the given parameters of the nozzle, to establish a change in the throughput of the feeder from the beginning of formation to the completion of dose formation. For the most part, in the existing designs of liquid product dosing modules, the change in throughput capacity of the nozzle is provided by valves._The geometric shape and the law of movement of the valve relative to the seat of the nozzle significantly affect the nature of the change in the throughput capacity of the nozzle. It was determined, that a conical shape is the effective shape of the valve, from the point of view of realizing the necessary law of change of throughput. (Gavva et al., 2023). The cone valve provides enough of its stroke to implement its law of movement by servo drives.

The feeder with a valve element for liquid products of the adaptronic dosing module consists of measuring container 1, nozzle 2 and valve 3 (Figure 2).

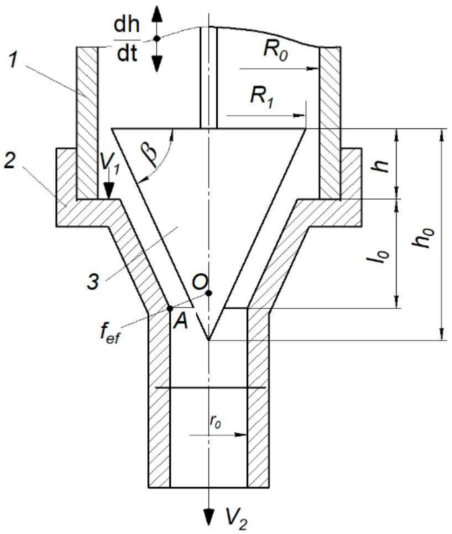


Figure 2. Calculation scheme of the feeder of the adaptronic dosing module with a conical valve for regulating the flow of liquid products:
1 – measuring container; 2 – nozzle; 3 – cone valve

Valve 3 is kinematically connected to a short-stroke servo drive through a rod. The upper inner part of the nozzle serves as a saddle._When designing such a feeder, the basic parameters are: the inner diameter of the nozzle d_0; angle β at the base of the cone valve and length l_0 of the seat base. The choice of nozzle diameter d_0 depends on the inner diameter of the neck of the consumer packaging (bottle) and the required capacity of the feeder.

Other geometric parameters of the nozzle valve are functionally related and are determined by the formulas:

$$R_1 = r_0 + \frac{l_0}{tg\beta} \quad ,(1)$$

where R_1 is the base radius of the conical valve;

r_0 – the radius of the internal cone of the nozzle;

$$h_0 = r_0 \cdot tg\,\beta + l_0 , \quad (2)$$

where h_o – valve height.

$$R_{0min} = \left(r_0^2 + R_1^2\right)^{0,5} , \quad (3)$$

where R_{0min} – the minimum value of the radius of the internal volume of the measuring container, determined from the condition of equality of the throughput capacity of the nozzle and the channel between the valve and the inner surface of the measuring container;

$$h_{max} = r_0\left(tg\beta - sin\beta\right), \quad (4)$$

where h_{max} – the maximum necessary movement of the cone valve, which ensures the equality of the throughput of all channels of the feeder.

To change the throughput of the feeder nozzle, h varies from 0 to h_{max}.

The law of displacement of the valve is defined as a function of the change in the capacity of the feeder

$$\frac{dh}{dt} = f\left(\frac{dQ_A}{d_t}\right), \quad (5)$$

Q_A – the throughput capacity of the nozzle in the feeder channel, the effective area of which is determined by the normal at point A to the surface of the cone valve.

That is,

$$Q_A = \frac{\pi}{sin^2\beta}\left(r_0^2 - \frac{\left(r_0 tg\beta - h\right)^2}{tg^2\beta}\right) \cdot \vartheta_A , \quad (6)$$

where ϑ_A -the average speed of fluid movement in the channel of the feeder, the effective area of which is the smallest one (point A).

The law of changing the capacity of the feeder, in order to achieve high indicators of dosing accuracy by weight method, depends on the physical and mechanical properties of the liquid product, the amount of the dose, the configuration of the consumer packaging and the performance of the adaptronic module.

The average speed of fluid movement in the feeder channel is determined based on the solution of the hydrodynamic equations.

The problems of hydrodynamics are aimed at finding functions of fluid flow rate, pressure (stress) and dynamic viscosity using systems of the Navier-Stokes equation, equations of flow continuity and additional holonomic connections that close the system. Having thus written the analytical model of fluid movement and assuming the assumption that the fluid is incompressible, moves in axisymmetric channels,_we will get partial differential equations that can be solved only by numerical methods. In this case, for a wide variation of the initial data, it is appropriate to use simulation modeling (CFD) using one of the Solid-Works – Flow – Simulation-2023 program packages.

During the simulation, the following assumptions were made: the liquid is incompressible and corresponds to a Newtonian liquid in terms of physical and mechanical properties, the valve and other parts of the feeder are made of rigid elements that do not deform under the action of hydrostatic load. The fluid movement in the axisymmetric design of the feeder is described by the equations embedded in the Solid Works program (Dassault Systems Technical Reference Solid Works Flow Simulation, 2023).

$$\frac{d\rho}{dt}+\frac{d}{dxi}\left(\rho\cdot U_i\right)=S_M^P; \tag{7}$$

$$\frac{d\rho\cdot U_i}{dt}+\frac{d}{dxi}\left(\rho U_i\cdot U_j\right)+\frac{dP}{dxi}=\frac{d}{dxi}\left(\tau_{ij}+\tau_{ij}^R\right)+S_i+S_{Ii}^P, \tag{8}$$

i=1,2,3*;* j=1,2,3;

$$\frac{d\rho H}{dt}+\frac{d\rho U_i H}{dxi}=\frac{d}{dxi}\left[U_i\left(\tau_{ij}+\tau_{ij}^R\right)+q_i\right]+\frac{d\rho}{dt}+S_iU_i+S_H^P+Q_H, \tag{9}$$

$$H=h\left(P,T,y\right)+\frac{U^2}{2}+k, \tag{10}$$

where U – fluid movement speed;

ρ – volume mass of liquid;

S_i – external force distributed by mass per unit mass

$$S_i=S_i^P+S_i^g+S_i^r, \tag{11}$$

S_i^P - the resistance of the environment;

S_i^g - gravity, $S_i^g=\rho\cdot g_i$;

S_i^r – inertial force in the direction of movement *i*;

H – total enthalpy of the local frame of reference;

h(P,T,y) – thermal enthalpy is determined at given pressure P, temperature T and components of the liquid mixture;

k – kinematic energy of turbulence;

S_M^P, S_{Ii}^P i S_H^P - are additional conditions for the interphase interaction of particles (Euler-Lagrange);

Q_H -_source or sink of heat per unit volume of fluid;

τ_{ij} - tensor of viscous fluid shear stress;

q_i - diffusion heat flow.

The energy equation for calculating the flow with a high Mach number can be written in the form

$$\frac{d\rho E}{dt}+\frac{d\rho U_i\left(E+\frac{P}{\rho}\right)}{dxi}=\frac{d}{dxi}\left[U_j\left(\tau_{ij}+\tau_{ij}^R\right)+q_i\right]-\tau_{ij}^R\frac{dUi}{dxi}+\rho\varepsilon+Q_H; \tag{12}$$

$$E = e\left(\rho, T, y\right) + \frac{U^2}{2}, \tag{13}$$

where $e\left(\rho, T, y\right)$ - integral energy at a given volumetric mass ρ, temperature T and concentration of the components of the liquid mixture y.

The viscous shear stress tensor for Newtonian fluids has the form

$$\tau_{ij} = \mu\left(\frac{dU_i}{dxi} + \frac{dU_j}{dxi} - \frac{2}{3}\delta_{ij}\frac{dU_k}{dxk}\right). \tag{14}$$

Accepting Boussineux's assumption, the Reynolds stress tensor has the following form

$$\tau_{ij}^R = \mu_t\left(\frac{dU_i}{dxj} + \frac{dU_j}{dxi} - \frac{2}{3}\delta_{ij}\frac{dU_k}{dxk}\right) - \frac{2}{3}\rho k\delta_{ij}, \tag{15}$$

where δ_{ij} – Kronecker's delta function;

μ – dynamic viscosity of the liquid

μ_t – turbulent viscosity.

To describe the change in turbulent and kinetic energy k and dissipation ϵ, we write down two additional transport equations

$$\frac{d\rho k}{dt} + \frac{d}{dxi}\left(\rho U_i k\right) = \frac{d}{dxi}\left[\left(\mu + \frac{\mu_t}{G_k}\right)\frac{dk}{dxi}\right] + S_k; \tag{16}$$

$$\frac{d\rho\epsilon}{dt} + \frac{d}{dxi}\left[\left(\mu + \frac{\mu_t}{G_\epsilon}\right)\frac{d\epsilon}{dxi}\right] + S_\epsilon; \tag{17}$$

where S_k, S_ϵ are defined as follows

$$S_k = \tau_{ij}^R\frac{dU_i}{dxi} - \rho\epsilon + \mu_t \cdot P_B;$$

$$S_\epsilon = C_{\varepsilon 1}\frac{\varepsilon}{k}\left(f_1\tau_{ij}^R\frac{dU_i}{dxi} + \mu_t \cdot C_B \cdot P_B\right) - C_{\varepsilon 2 f 2}\frac{\rho\varepsilon^2}{k}, \tag{18}$$

where P_B – turbulent generation from buoyancy forces

$$P_B = -\frac{g_i}{\sigma_B} \cdot \frac{1}{\rho} \cdot \frac{dP}{dxi}, \tag{19}$$

where g_i – the component of the acceleration of gravity in the direction x_i;

C_B is a constant, determined from the condition: $P_B>0$, $C_в=1$, otherwise $C_в=0$.

$\sigma_в=0.9$ – the constant is accepted empirically.

$$f_1 = 1 + \left(\frac{0,05}{f_\mu} \right)^3, \; f_2 = 1 - exp\left(-R_T^2 \right); \tag{20}$$

where $C_\mu, C_{\varepsilon 1}, C_{\varepsilon 2}, \sigma_k, \sigma_\varepsilon$ – constants are accepted by the Solid Works Flow Simulation program for drinking water. $C_\mu = 0,09$; $C_{\varepsilon 1} = 1,44$; $C_{\varepsilon 2} = 1,92$; $\sigma_k = 1$; $\sigma_\varepsilon = 1,3$.

Simulation modeling involves developing a graphic model in the Solid Works program and placing it in the Flow–Simulation subprogram. The area of calculation is limited by the contours of rigid parts of the feeder. The research consisted of three thematic approaches:

- the first approach was based on determining the hydrodynamic parameters of fluid movement in the intervalve channel under the condition that the base of the seat l0 is a constant value, and the angle β at the base of the cone varied from 30 to 60º;
- the second approach was based on determining the hydrodynamic parameters of fluid movement in the intervalve channel under the condition that the angle β at the base of the cone is a constant value, and the seat base l0 varies from 5 mm to 25 mm;
- the third approach was based on the recognition of the influence of the type of surface of the base of the cone valve and the hydrodynamic parameters of the fluid movement. At the same time, the following surfaces were considered: conical, spherical convex and concave.

The initial data for the calculations are: liquid – drinking water, volume mass ρ=1000 kg/m^3; temperature t=20 ºC; feeder throughput – 500000 mm^3/sec; the inner diameter of the feeder nozzle d_0=20 mm. Calculations were performed for different positions of the cone valve when it is moved step by step from $0 < h \le h_{max}$.

Experimental installation

The adequacy check of the results of the analytical simulation of movement in the feeder channels was performed on the created experimental installation (Figure 3, Figure 4).

The experimental instalation consists of a waste tank 1, which is closed by a cover 2. The cover has a built-in funnel 3, through which liquid is supplied to maintain a constant level in the waste tank 1. To control the level of liquid in the waste tank, a level sensor is installed, the signal from which is sent to the shut-off valve liquid supply. A servo-pneumatic actuator 4 is also installed on cover 2, the rod of which is connected to conical valves 13 (Figure 5).

The external geometric dimensions of the valve correspond to the dimensions of the seat 14. The tightness of the connection of the valve seat to the flow tank is ensured by installing a seal 15. The amount of movement of the valve relative to the seat is ensured by changing the air pressure in the cavities of the pneumatic cylinder using a pressure regulator with proportional control 11 (Figure 4), which is connected to the compressed air supply pipeline 12._The weight of the liquid entering the consumer packaging 7 per unit of time is measured by strain gauges 6. Strain gauges 6, a pressure regulator 11 and an electric pressure sensor transmit information through an analog-to-digital converter 8 to a computer 10, which forms a digital database using special software data.

The research was carried out with the following initial data: liquid – drinking water; water temperature -20 ºC; the height of the liquid column in the flow tank H=0.128 m; inner diameter of the nozzle d_o=20 mm; angle at the base of the cone β=60º; the length of the saddle base l_0=15 mm.

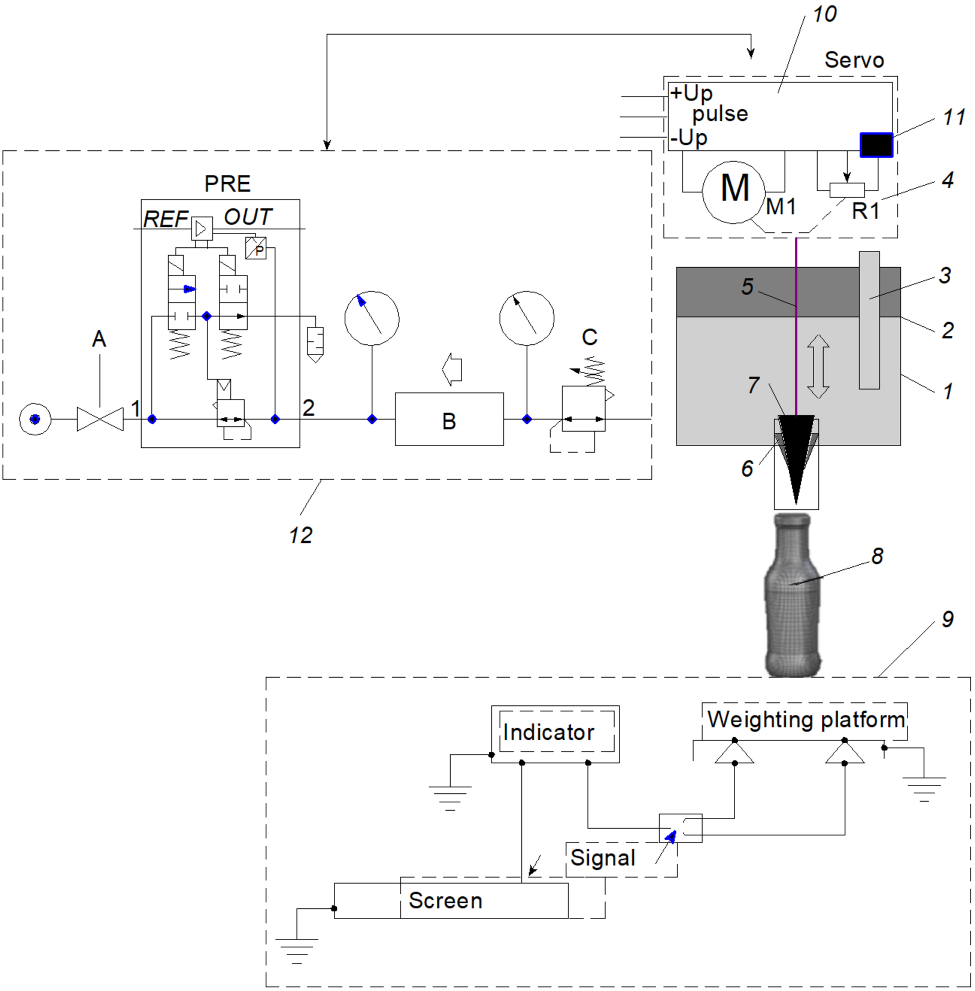


Figure 3. Schematic diagram of the experimental installation for researching the throughput capacity of the feeder of the adaptronic dosing module with a conical valve for distributing the flow of liquid:
1 – flow tank; 2 – cover, 3 – watering can;
4 servo-pneumatic drive; 5 – rod; 6 – nozzle saddle; 7 – cone valve;
8-consumer packaging; 9 – tensometric weighing system;
10 – analog-digital converter; 11 – electronic cone valve movement sensor;
12 – pressure regulator with proportional control

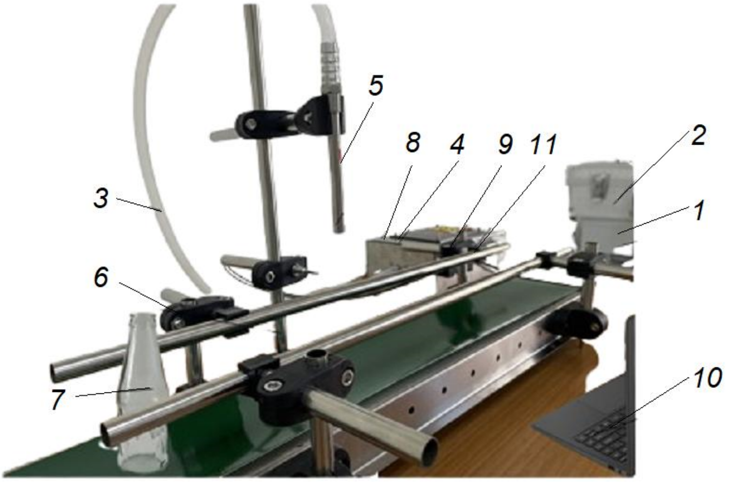


Figure 4. Experimental installation for researching the throughput capacity of the feeder of the adaptronic dosing module with a conical valve for distributing the flow of liquid:
1 – waste tank; 2 – cover; 3 – watering can,
4 – servo-pneumatic drive; 5 – nozzle; 6 – tensometric weighing system;
7 – consumer packaging; 8 – analog-digital converter; 9 – power supply unit;
10 – computer; 11 – pressure regulator with proportional control; 12 compressed air pipelines

Figure 5. Design of the feeder nozzle of the adaptronic fluid dosing module:
13 – valve of conical shape; 14 – saddle with nozzle; 15 – sealing ring

Sequence of experiment

The experiment was conducted in the following sequence. At the initial moment, the valve closes the nozzle channel, the flow tank is filled with liquid up to the level sensor, a container is installed under the nozzle on the strain gauge. The capacity is pre-weighed. Through the computer, the law of movement of the valve at a given step is set. In that case, it is 2, 4, 6, 8 and 10 mm. The power system is turned on, the valve moves to the specified height, the liquid moves into the container._To stabilize the liquid level in the waste tank, water is supplied through a funnel and a pipeline. The liquid is moved into the container for 5 seconds, after which the system is turned off, the valve closes the nozzle channel, and the strain gauges and the computer record the weight of the gross liquid and container._The obtained value of the weight of the liquid without the container is divided by 5 to determine the throughput of the nozzle at the given position of the valve. After conducting preliminary studies, it was established according to the Student's criterion that for p=0.95 it is necessary to repeat the experiment N=4. After statistical processing of experimental data, the results are entered into a computer to construct a graphical interpretation.

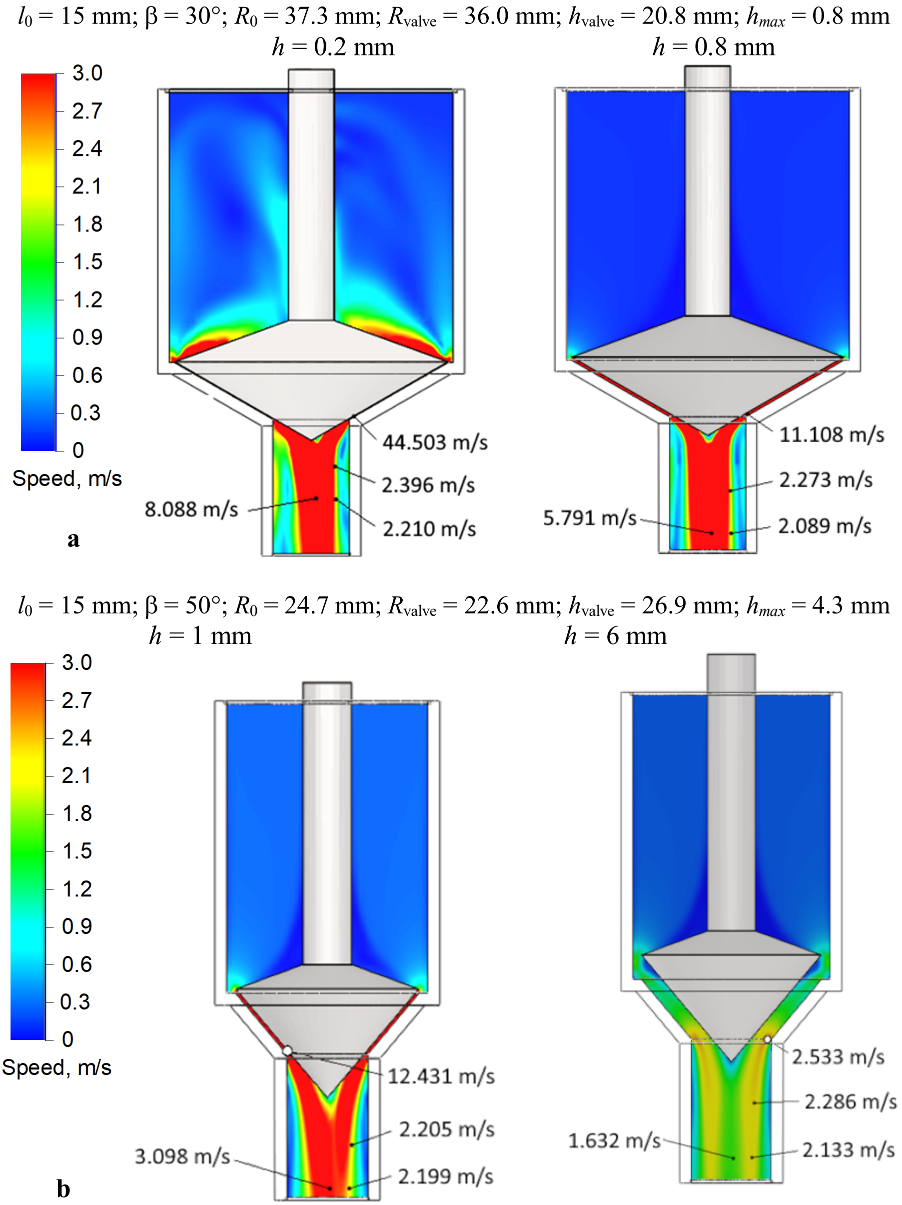
Results and discussion

Figure 6 shows the interpretation of the functional dependence of the change of the effective area of the intervalve channel from the height of the lifting valve only of the nozzle seat.

Figure 6. Change in the effective cross-sectional area of the liquid channel of the feeder with a cone valve (β=60°; r_0=10 mm) from the movement of the valve

The character of the obtained dependence is close to a linear function, which makes it possible, with high reliability, to implement the desired valve motion law with a servo drive. The law of valve movement is determined from the condition of ensuring the productivity of the module, the size and accuracy of the product dose and its physical and mechanical characteristics.

Figure 7 shows the results of simulated modeling of the movement of liquid products in the intervalve channel of the feeder for different values of the angle at the base of the valve cone. The results of the calculations are a change in the values of the fluid movement speed at different points of the feeder and at different positions of the valve relative to the nozzle seat. The generalized results of changes in the speed of fluid movement at the exit from the intervalve channel are shown in the form of 3D graphs.



l_0 = 15 mm; β = 30°; R_0 = 37.3 mm; R_{valve} = 36.0 mm; h_{valve} = 20.8 mm; h_{max} = 0.8 mm

h = 0.2 mm; h = 0.8 mm

l_0 = 15 mm; β = 50°; R_0 = 24.7 mm; R_{valve} = 22.6 mm; h_{valve} = 26.9 mm; h_{max} = 4.3 mm

h = 1 mm; h = 6 mm

Figure 7. Change in the field of the velocity vectors of the movement of liquid products in the intervalve channel of the feeder for different values of the angle β at the base of the valve cone: a – 30°; b – 50°; c – 60°.

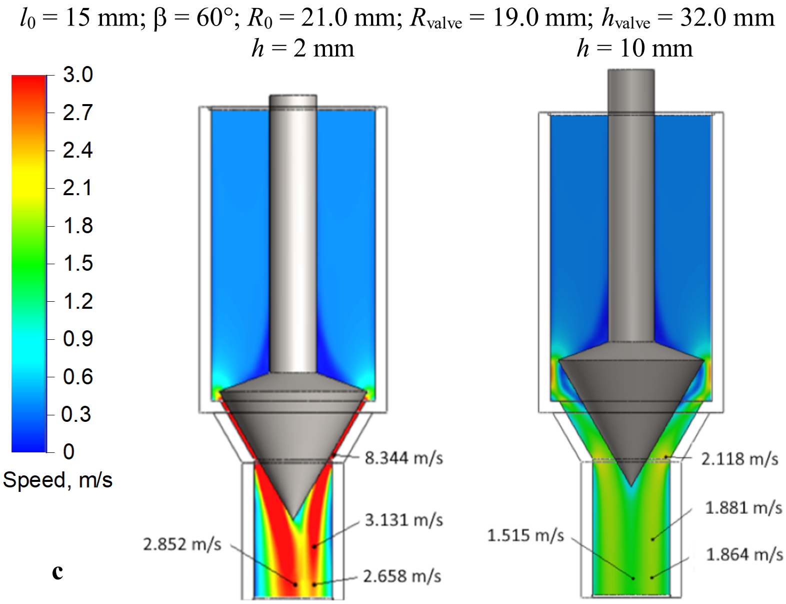


Figure 7 (*continue*). Change in the field of the velocity vectors of the movement of liquid products in the intervalve channel of the feeder for different values of the angle β at the base of the valve cone: a – 30º; b – 50º; c – 60º.

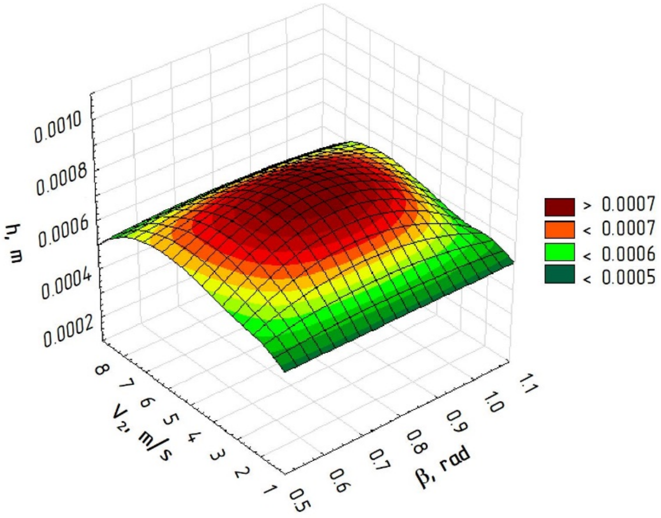
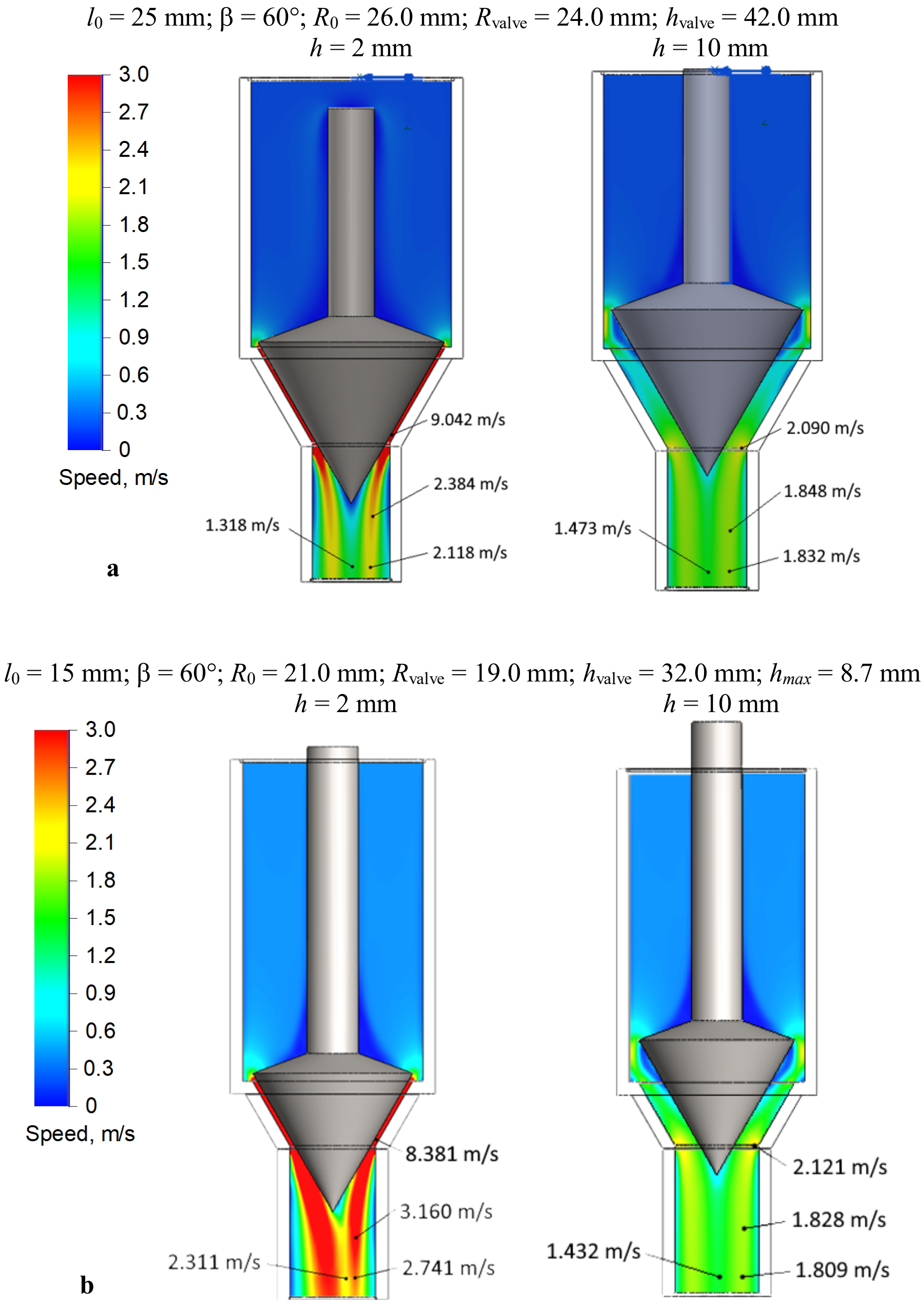


Figure 8. Change in the speed of fluid movement at the exit from the intervalve channel at different values of the angle at the base of the valve cone



l_0 = 25 mm; β = 60°; R_0 = 26.0 mm; R_{valve} = 24.0 mm; h_{valve} = 42.0 mm

h = 2 mm h = 10 mm

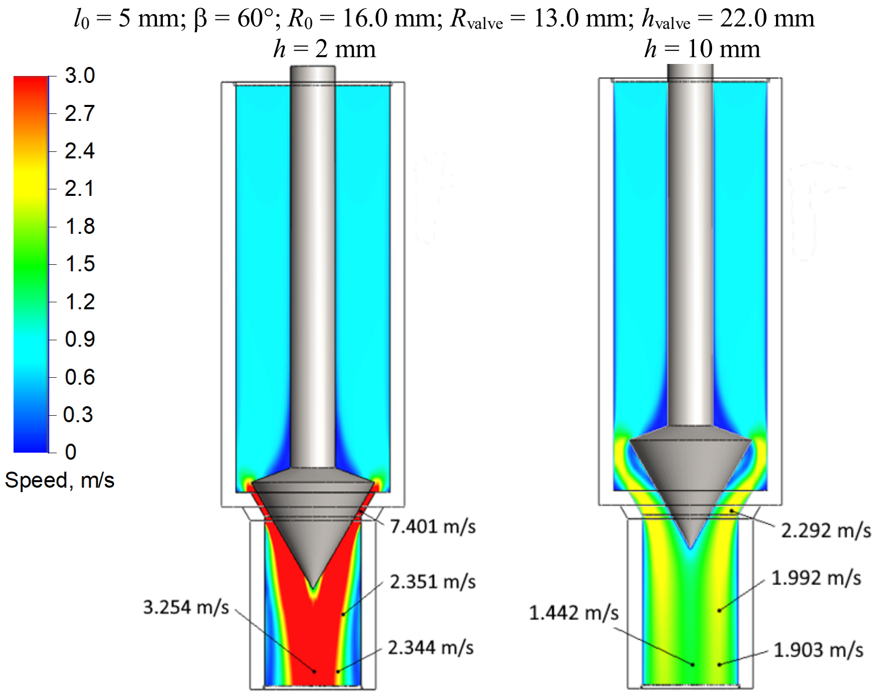
a

l_0 = 15 mm; β = 60°; R_0 = 21.0 mm; R_{valve} = 19.0 mm; h_{valve} = 32.0 mm; h_{max} = 8.7 mm

h = 2 mm h = 10 mm

b

Figure 9. Change in the field of vectors of the speed of movement of liquid products in the intervalve channel of the feeder for different values of the base of the saddle: a – l_0=25 mm; b – l_0=15 mm; c – l_0=5 mm



c

Figure 9 (*continue*). Change in the field of vectors of the speed of movement of liquid products in the intervalve channel of the feeder for different values of the base of the saddle: a – l_0=25 mm; b – l_0=15 mm; c – l_0=5 mm

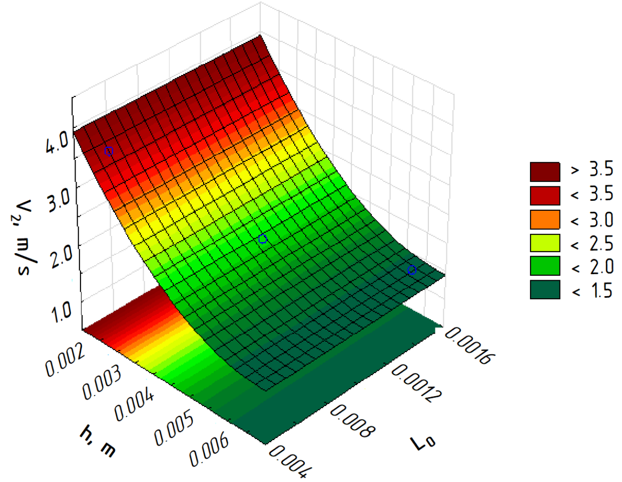
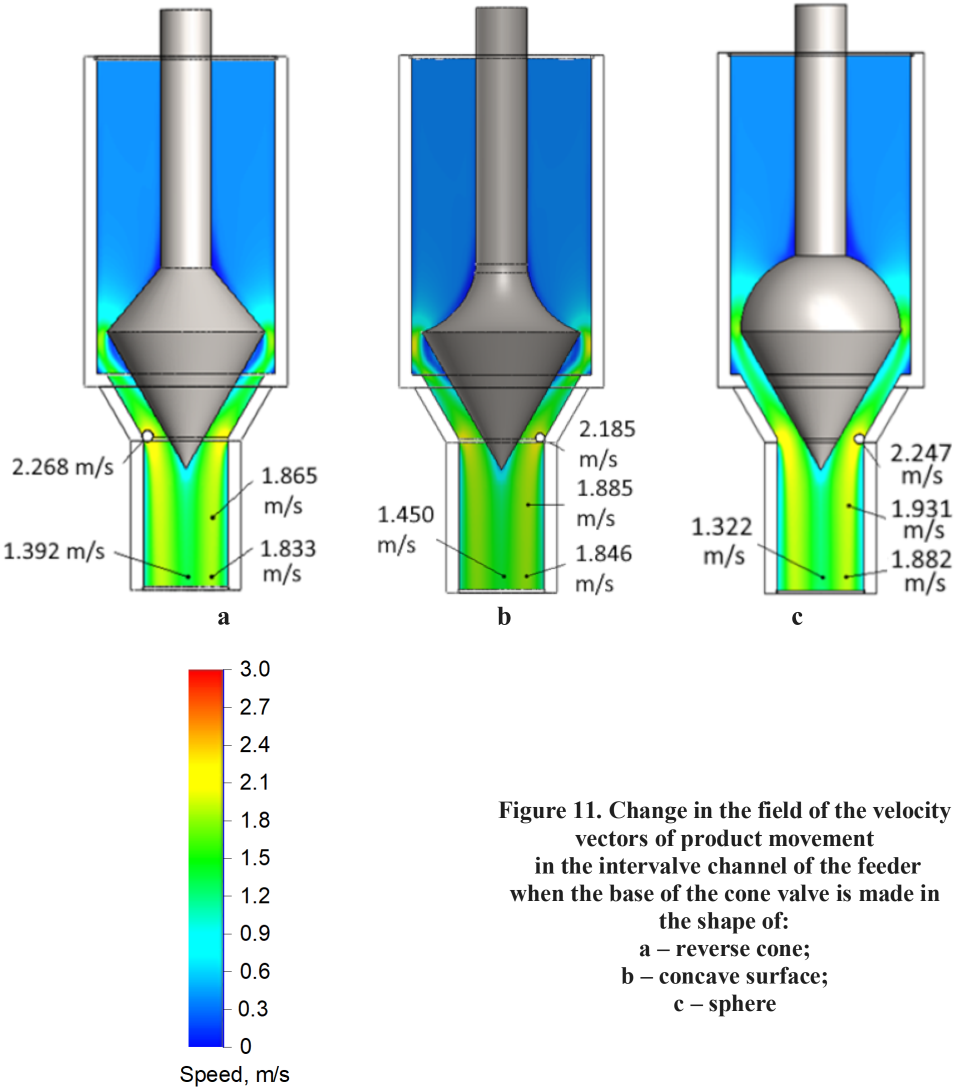


Figure 10. Generalized results of simulated modeling of fluid movement in the intervalve channel when changing the nozzle seat base

The analysis of the results of the simulation makes it possible to state that the execution of the conical valve with an angle at the base of 50–60° is the most rational, because it provides the maximum allowable stroke of the valve (7–10 mm), which makes it possible to effectively implement the given laws of changing the throughput of the feeder with servo drives. Along with this, it is important to eliminate possible fluid turbulence in the intervalve channel and at the exit from the seat. Such conditions are realized also when the angle at the base of the valve cone is within 50–60°.

The rational design of the valve feeder also depends on the length of the nozzle seat base. Figure 9 shows a graphical interpretation of the results of simulated modeling of fluid movement in the intervalve channel of the feeder for different values of the saddle base, and Figure 10 shows their generalizations.



a b c

Figure 11. Change in the field of the velocity vectors of product movement in the intervalve channel of the feeder when the base of the cone valve is made in the shape of:
a – reverse cone;
b – concave surface;
c – sphere

The results of the study show that the length of the base of the saddle makes it possible to stabilize parallel fluid flows and minimize the factors of the emergence of turbulence centers. And therefore, it is appropriate to choose the length of the saddle base within 20–25 mm at $\beta=50–60^{\circ}$.

As can be seen from Figure 7 and Figure 9, the contact of the liquid with the surface of the base of the valve cone, which is located perpendicular to the body of the feeder, creates a slight decrease in the pressure of the liquid, which leads to the effect of its reverse movement.

All this affects the parallel laminar mode of liquid movement, which must be implemented in dosing systems to ensure the specified accuracy of dosing and duration of product storage._To eliminate this phenomenon, it is appropriate to replace the flat surface of the base of the cone with a convex or concave one.

Figure 11 shows the results of the base of the cone in the form of: reverse cone; concave and convex sphere.

From the point of view of fluid flow stability, the obtained results demonstrate that the best result is achieved when the surface of the base of the cone is made in the form of a sphere with a radius equal to the radius of the base of the cone $R_{sp}=R_1$. Along with this, on the graphic images of the change in the speed of movement of the liquid in the feeder, it can be seen that at the places where the liquid enters the intervalve channel, there is additional resistance, that is, it is a zone of possible formation of turbulence.

The next negative factor is the formation of an annular cross section of the liquid flow after its exit from the valve channel into the cylindrical nozzle. To stabilize the flow of liquid across the nozzle, it is possible to increase the length of the nozzle or make the valve in the form of a truncated cone (Figure 12).

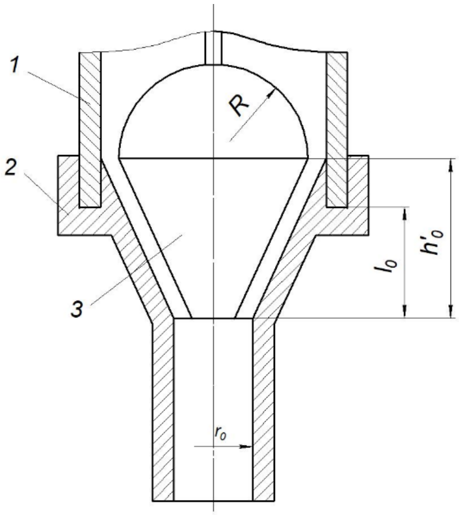


Figure 12. Improved design of the feeder valve of the adaptronic liquid product dosing module: 1 – measuring capacity; 2 – nozzle; 3 – cone-spherical valve

The reliability of the results obtained by analytical and simulation modeling is confirmed by the results of experimental studies (Figure 13). The error in the throughput capacity of the valve feeder for different positions of the valve, relative to the nozzle seat, did not exceed 4.3%.

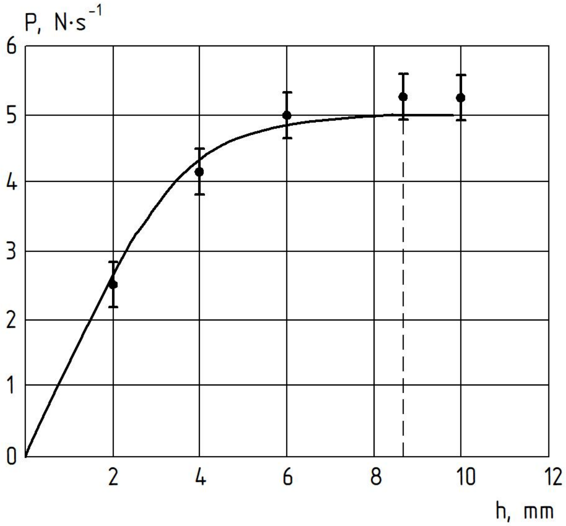


Figure 13. Change in the throughput capacity of the valve feeder at different positions of the valve relative to the nozzle seat

Conclusions

1. The hydrodynamic phenomena of fluid movement in valve feeders are described by complex nonlinear differential equations, with the help of which it is practically impossible to choose rational values of the geometric parameters of the valve, and therefore it is appropriate to use simulation modeling based on computational fluid dynamics (CFD) for the corresponding group of liquid products.
2. On the basis of the analytical dependencies between the parameters of the valve and the feeder seat, the simulation of fluid movement in the intervalve channel in the program Solid Works – Flow – Simulation 2023, it was established that according to the criteria of the minimum dimensions of the feeder, the possibility of implementing the given law of changing the throughput and eliminating possible cells turbulence, it is recommended to take the angle at the base of the valve cone in the range of 50o–60o, and the base of the nozzle seat in the range of 20–25 mm.
3. During the movement of the liquid in the valve feeder, three negative factors affecting the parallel laminar movement of the liquid were also found: reverse movement of the liquid when it comes into contact with the surface of the base of the valve cone; turbulence cells at the entrance of the liquid into the valve channel and the tubular form of the liquid flow in the nozzle. These negative factors can be eliminated by using a ball-conical valve with a truncated top.
4. The obtained research results need clarification for a wide range of liquid products with different values of physical and mechanical properties.

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