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SYNTHESIS OF THE CONTROL SYSTEM FOR THE POSITIONING PNEUMATIC DRIVE OF SHUT-OFF FITTINGS ACCORDING TO THE CRITERIA OF TECHNOLOGICAL EFFICIENCY

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This paper reports the new design of an experimental bench to study the effectiveness of the positional drive control system of shut-off fittings. For research, the operating modes of the disk flap and ball valve, based on proportional elements with feedback (4–20 mA), were programmatically formed and described.

The mathematical model of control over shut-off devices has been analytically described on the example of a disk rotary valve with the possibility of further analysis of individual stages in accordance with the accepted assumptions. The operating control signal is justified with a serial asynchronous interface with an offset operating range of permissible values of –16.0 mA.

Separate stages in the operation of the synthesized shut-off fittings based on accepted assumptions have been described. Measurements were performed for disc damper angles of 30°, 60°, 90° by variable value of the pressure control signal (1...4 bar) with sampling of measuring indicators for the control system in real time. The results obtained experimentally confirmed the adequacy of numerical modeling regarding the study of the disk rotary inter-flange valve, as well as preliminary assumptions in the mathematical model. Data were obtained to test the efficiency of controlled shut-off fittings (V-shaped ball valve, disc rotary inter-flange valve) at a sugar factory. The average angle of rotation for a ball is 17.61 degrees; the average value of the vapor temperature after cooling is 130.91 °C (subject to a given value of 130.0 °C). The deviation of the set value is 0.7 %. The average value for the angle of rotation of the disc damper at 43.0 degrees showed the largest deviation of technological parameters of 1.45 %

Keywords: electro-pneumatic positioner of the shut-off device, characteristics of the mechanical-drive control system of the positioner, disc damper, ball valve with V-neck, sugar production, technological efficiency of operational processes

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1. Introduction

The functioning of complex technological facilities is largely determined by the quality and reliability of the equipment. A relevant task for the efficient operation of technological equipment is to improve the quality of control devices for shut-off pipe fittings. Typically, such tasks are implemented by improving the quality of individual elements, parts, assemblies that are combined within a single technical system. However, as practice shows, for the working circuits of technological equipment in food production, the expected effect of increasing the level of technological efficiency is not always additive.

The variability of the initial characteristics that determine the quality of the positional drives of shut-off fittings is due to the emergence of new “system qualities” during the technical combination of heterogeneous elements. New synthesized technical solutions for valve actuators can both have a positive effect on the quality of the integrated technological system and be the cause of a violation of the safety of operating facilities.

Sources of increased danger are technical solutions for shut-off fittings serving sugar production facilities, chemical, pharmaceutical, and packaging industries, and others.

A relevant task is the combination of heterogeneous (mechanical, electrical, pneumatic) control elements into a single technical system – a drive with specified technical characteristics. An important area of research is to solve the problems of synthesis of systems "positional pneumatic actuator – shut-off fittings – control system" as the main systems that enable the reliability of the operation of technological equipment.

The most important indicators of the quality of the positional pneumatic drive control system of shut-off fittings are tightness, reliability, safety, as well as speed, which determine the time of closing the pipeline for an emergency.

To enable the required speed, the shut-off fittings are controlled by high-speed pneumatic actuators with electric control, that is, positional controls. The characteristics of the combination of elements within the synthesis of control systems with shut-off fittings are the power parameters: torque and forces, the values of which are recorded in the nomenclature catalogs. Technical integration of the combination of shut-off fittings with high-speed drives, without taking into consideration technological regulations, leads to inconsistency in actual and normalized (calculated) power characteristics. This inconsistency is the cause of significant loads in the shut-off fittings on the side of the drive, which increases the risk of systems leaving the working condition.

Along with the technical modernization of the elements of positional pneumatic actuators of shut-off fittings, the priority is to supplement the control systems with damping devices. Such devices are designed to dampen the excess stored energy of the system with a reduction in loads, which supports the energy efficiency of the system.

Thus, an actual top priority task is to increase the level of technological efficiency of the positional pneumatic drive control system of shut-off fittings for reliable, inexpensive, and compact equipment.

2. Literature review and problem statement

During the operation of pipeline networks of technological circuits at food production enterprises, and others, it is necessary to constantly maintain a predetermined pressure regime at the inlet and outlet of pumping units. The performance of the equipment depends on it and the number of its unforeseen stops decreases. The simplest method for regulating the hydrodynamic mode of operation of technological pipelines today is the use of controlled shut-off fittings: disc dampers, ball valves, saddle valves, etc. Taking into consideration all the advantages of shut-off and control valves, there is one significant drawback – a nonlinear static characteristic, which complicates the adjustment process. One of the actual directions for solving this drawback is the correct choice of an effective drive control system. In work [1], the main hydromechanical characteristics of a rotary valve and its influence on the flow of liquid are investigated. But the effect of changing the closing time of the closing element, the disc, on the transition process of the pipeline is not substantiated. The static characteristic of the rotary valve given by the authors is similar to the static characteristic of the latch, so it is advisable to expand the study towards justifying the change in the time of the full stroke of the rotary valve. A critical analysis of the nonlinear dynamics of the butterfly damper, which is given in [2], focuses the researchers' attention only on the dynamics of switching on and off the valve and its nonlinear reaction during the perturbation of the working system. At the same time, the complex interaction between the drive, hydrodynamic and mechanical forces is investigated only by certain stages of work. This approach can cause difficulties in tracking the effectiveness of the valve in assembling with a drive.

A variant of the advanced analysis of automation systems for the elements of the pipeline shut-off and control system is valve designs described in [3]. The description is given of the different types of drives, such as hydraulic, pneumatic, and electric drives. A table of performance recommendations is provided, depending on the size and pressure class of the valves. However, the studies substantiate the characteristics of work only for unidirectional ball valves and do not describe the problems of drives during factory tests.

In this case, a qualitative description of full-scale tests during the operation of shut-off fittings in product pipelines is described in [4]. The authors carefully describe the tests of the accuracy and repeatability of the positioning of the linear pneumatic cylinder in the composition with the ball valve, without paying attention to the analysis of rotary drives. In addition, the fixation of the location of the working link was carried out by an optical sensor of linear displacement, which leads to significant measurement errors.

For such an object as butterfly valves, work [5] describes, in addition to automatic control tools, a control syste. The authors insist on placing proportional controls on the control path. The application of such solutions in practice will require the development of universal automatic control systems for each specific technological task, which is a disadvantage of the proposed approach.

Examples of mathematical and statistical research on cavitation processes in controlled shut-off fittings are given by the authors of work [6]. The study focuses on the phenomenon of cavitation in the spool valve for the Aqua Drive system. However, an insufficient description of the control system for the contours of the metered supply of chemical agents does not make it possible to use the proposed method on other technological systems [7]. It is the solution of complex problems of theoretical and physical modeling of control systems in conjunction with shut-off devices, as noted by the authors of [8], is a relevant area in the development of drive synergy with elements of pipeline fittings.

The disadvantages identified from sources [4–7] include the complexity of the design 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 provided dosing ranges and the unsuitability of the same type of equipment for the dosing of media with different physicochemical properties. The design of dispensers is also affected by the narrow functionality, expressed in the absence, in a number of designs, of the remote control means of operational reconfiguration and regulation of their initial parameters.

The results of monitoring the operation of an electric ball valve, given in [8], by using three-dimensional simulation models showed the possibility of using control circuits without feedback but there remained questions related to the effectiveness of using the proposed shut-off device in various technological processes.

The processes of efficiency of shut-off pipe fittings are described in [9]. The paper discusses numerical modeling to observe flow patterns and measure flow oscillations. The limitations associated with the specific sizes of the control hole being investigated are noted. The above results, unfortunately, do not describe the structure of the working flow in the control values, and therefore cannot be used in pipeline fittings with other sizes.

The method of partial placement of elements of pipeline fittings along the length of the entire pipeline, proposed by the authors of [10], is used quite often. However, for the functional parameterization of the described stabilizing controllers, which support the technological regulations of the technological process, this is a rather difficult task. These problems prove that physical modeling [11] helps in solving complex problems of this type. Heuristic tools for modeling control systems, including electropneumatic ones, the results of which are given in [12], are combined with more traditional approaches. For example, the method of statistical analysis is described, which helps in solving complex problems of synthesis of the control object and the control system with feedback. It should be noted that the development of optimal methods for researching a technical system has both advantages, for example, reducing the time of equipment analysis, and forms disadvantages associated with the processing of a large array of data.

An example of solving problems with processing large amounts of experimental data is covered in [13]. The work focuses on practical and analytical research on monitoring the cavitational behavior of the valve during commissioning. For the formation of static characteristics of the functioning of various valves, the authors' method of controlling the location of the shut-off element without cavitation, flow rate, and pressure is used. As a result, the authors do not pay attention to the recommended operating modes of shut-off fittings based on the results of the study.

The study of computer control over the intake and exhaust valves in operation is carefully described in [14]. The main source of energy-consuming pumping losses can be reduced by controlling the valve timing and valve life in combination with a software-controlled process. Unlike previous works, the authors do not cover assumptions for mathematical modeling.

In [15], numerical and experimental studies of different positions of the control valves were carried out and the control system with feedback was carefully described to control the current parameters. The results of the work are useful for justifying the choice of controls for positional pneumatic systems. However, that paper does not take into consideration hydraulic components.

Regarding the conditions for the formation of a control signal by introducing an analytical function, the description is given in [16]. The authors recommended algorithms for controlling the positional drive based on experimental tests. Note that one model of the control system is described and the change in the speed modes of movement of the working flow in certain complex sections of the pipeline is not taken into consideration. In [17], methods for managing the performance of the working environment both under stationary mode and transient modes in comparison with traditional control are formed. The lack of experimental research limits the use of these methods on real equipment. The above description of the control and measuring equipment [18] provides recommendations for the choice of digital flow meters and control valves in the pipeline network. The authors of the work do not report the results of research in combination with the work of the control elements of the pipeline network. Namely, work [19], which reports the analysis of flow-type shut-off elements with automation tools, makes it possible to partially supplement the previous descriptions. However, the work shows significant limitations regarding the input parameters and assumptions.

The above review gives grounds to argue that it is expedient to conduct a study on the effectiveness of the control system of the positional pneumatic drive of shut-off fittings. In addition, by applying the methods of empirical research, it is possible to obtain the results of describing the adjustment of the costs of the working environment according to the specified characteristics of the technological regulations in actual production.

3. The aim and objectives of the study

The aim of this study is the synthesis of the control system of the positional pneumatic actuator of shut-off fittings based on electro-pneumatic systems with enhanced characteristics of technological efficiency. This will make it possible to reduce the energy intensity of shut-off fittings, simplify the design, and facilitate control over the process by controlling the working cross-section in the pipeline.

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

– to design an experimental bench to study the efficiency of the positional drive control system of shut-off fittings and programmatically set the operating modes of the disc damper and ball valve, based on proportional elements with feedback (4–20 mA).

– to build mathematical models for controlling shut-off devices and to carry out research of positional control modules for elements of shut-off fittings;

– to analyze the individual stages of operation of the synthesized devices of shut-off fittings based on accepted assumptions;

– experimentally in production (full-scale experiment) to test the efficiency of the controlled shut-off fittings. Namely, a ball valve with a V-neck and a disc damper based on a positional pneumatic drive. To investigate the effectiveness of the control system in relation to the characteristics of the working environment in the technological process at a sugar factory.

4. The study materials and methods

The object of this study is shut-off fittings with a positional pneumatic actuator. The subject of the study is the operational parameters of shut-off fittings with the control system as part of the technological equipment. The assumptions adopted in the studies are based on the current national standards (DSTU), implemented according to international standards (ISO) and the European system (EN). The main hypothesis of the study is the search for ways to increase the level of technological efficiency of the control system for the positional drive of shut-off fittings. Mathematic modeling is based on elements of pneumatic automatics for shut-off fittings, deriving a system of equations that describe the operation of structurally similar elements and their further use in the automatic control system.

The mathematical and statistical results, obtained during experimental and theoretical studies, are based on the applied theory of hydrogasodynamics and dynamics of machines in combination with control systems. For mathematical models, the study of dynamic parameters in shut-off controlled elements is also used: methods of numerical solution of systems of differential equations and methods of synthesis of control systems of the positional drive.

The choice of design parameters for a shut-off fitting device is justified, aimed at improving the metrological characteristics of the automated control system of the pipeline network. The research takes into consideration the static as well as dynamic characteristics of the system for combining the positional drive with the elements of shut-off fittings. For the experiments, new schematic diagrams for controlling positional pneumatic actuators of shut-off fittings have been developed, which enable the implementation of various laws of motion of the original controlled link. A number of typical designs of shut-off devices with positional pneumatic drives based on technological equipment for sugar production have been improved. The method of checking the shut-off devices for the energy costs of their drives and determining the change in technological parameters to regulate the process of supplying Newtonian liquids was employed.

The approach to adjusting the work of the shut-off element, the disk rotary valve, in accordance with works [2, 4], is described by the scheme in Fig. 1. Analysis and synthesis of mathematical models for positioning systems of the output links of shut-off fittings have a more auxiliary character and does not exclude the need for mandatory field research. By synthesis, we mean mathematical and physical modeling of processes in a pipeline network with shut-off fittings. To establish the dependence on the change in cost characteristics of the control signal, a series of studies was carried out. A generalized scheme for the experimental shut-off device has been built, with the fixation of intermediate positions of a disc damper according to the operational regulations.

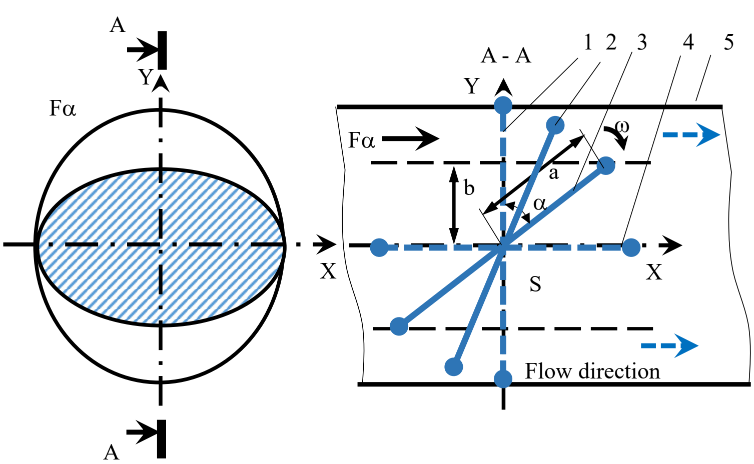


Fig. 1. Scheme of the projection of the valve onto a plane that is perpendicular to the longitudinal axis of the shut-off element: 1 – location of the rotary disk for 0° with fixation; 2 – location of the rotary disk for 30°; 3 – location of the rotary disk for 60°; 4 – location of the rotary disk for 90°; 5 – the inner surface of the passage channel of the shut-off element

In order to study the effectiveness of control and operation of shut-off devices, on the basis of technological pipelines in the production of sugar, we have designed an experimental bench. This made it possible to investigate the positioning accuracy of the positioning drives of shut-off fittings and the repeatability of working out shut-off elements for various pipeline networks. The structure of the bench provides the possibility to compare and study flow characteristics for the same type of shut-off devices. The structure of the bench makes it possible to change the working conditions of the bench elements, registering the pressure in the pipeline with liquid and compressed air, and setting the temperature of the working fluids. Separately, it is possible to set the laws of motion for shut-off elements using a control system.

Accepted assumptions: the area of the pipeline with a shut-off device, a rotary disc damper, subject to the control of the positional pneumatic drive, changes unevenly. To reduce pressure surges that occur during a change in productivity and the supply of a working fluid medium, it is necessary to set intermediate positions of the disk of the shut-off element. In order to change the location of the shut-off element, which occurs step by step, the number of stops for the disk is regulated by a given intensity of growth of the area of the passage section at the time of opening the valve.

The simplifications adopted in this study: when turning the valve, its projection onto a plane that is perpendicular to the longitudinal axis of the shut-off device is ellipsoidal (Fig. 2) with an area: $S=\pi\cdot a\cdot b$, where, respectively, $b=a\cdot\cos\alpha$, where b is the projection of a given radius of the disc damper onto the vertical (the radius of the valve is assumed to be equal to the inner radius of the body of the shut-off device).

Note that the cross-sectional area for the internal cavity of the shut-off device with a disc rotary damper: $F_0=\pi\cdot r^2$, and at $r=a$, we have $F_0=\pi\cdot a^2$.

The cross-sectional area of the shut-off device of the disc rotary damper at the time of opening at a given angle α: $F_a=F_0-S_d=\pi\cdot a^2(1-\cos\alpha)$.

That is, the area of the ellipse S_d through the radius of the valve a and the angle of its rotation α: $S_d=\pi\cdot a^2\cdot\cos\alpha$.

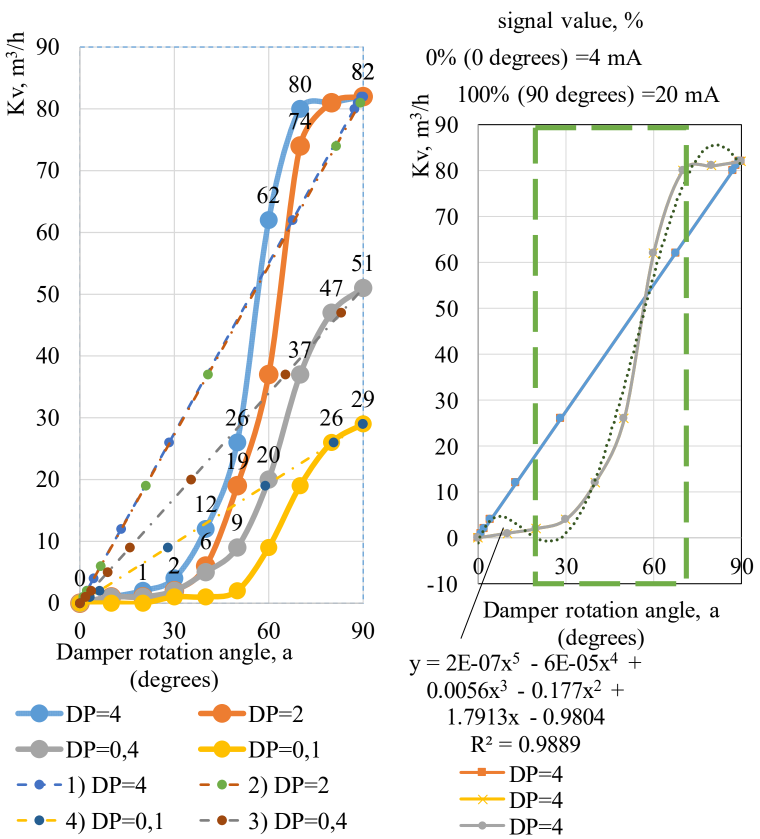
Suppose: $\alpha=0$, $\cos\alpha=1$, $F_a=0$; if $\alpha=90°$, $\cos\alpha=0$, $F_a=\pi\cdot a^2$. Accordingly, the rate of change in the flow cross-sectional area depending on the angle α:

$$\frac{dF_\alpha}{d\alpha}=\pi\cdot a^2\sin\alpha. \quad (1)$$

Subject to a constant rotational speed for the disc damper at the time of opening, that is, when the condition applies: $\frac{\partial\alpha}{\partial t}=\text{const}$, the rate of change in the cross-sectional area $\frac{dF_\alpha}{d\alpha}$, will depend on the change in the angle of rotation α for the disc damper for uneven distribution. Accordingly, during the study, it was assumed that the intensity of increasing the cross-sectional area at the beginning of opening the valve is minimal, at the end of the process it will be maximum (opening 90°). The change in the pressure of the working research medium is determined by the degree of opening of the disc damper.

The study of the effectiveness of the position pneumatic drive control system of shut-off fittings is planned on the basis of disc rotary dampers and ball valves and a saddle valve. For experimental studies, the method of a fully factorial experiment was chosen by estimating the opening time of the shut-off element, the value set for the angle of rotation (or passing gap), the flow rate of the working medium, the magnitude of the control signal from the positional pneumatic drive.

Experimental factors (Fig. 2) in the experiment on the bench: the flow rate of the working medium, the switching time of the control system of the shut-off element, the flow rate, and the pressure of the positional pneumatic drive system.



a *b*

Fig. 2. Characteristics of throughput control measurement for rotary valves DN depending on the angle of rotation of the disk: *a* — change in flow rate of the working medium from the angle of rotation of the working valve; *b* — rational zone of influence on the control signal

According to Fig. 2, *a*, the values on plot field 1...82 specify the throughput of the rotary valves, such as DN 40, depending on the angle of rotation of the working valve disk. Nominal diameter DN is a parameter that is used for pipeline systems as a characteristic of the connected parts of fittings. DP is the hydraulic resistance of disc dampers (bar), a tabular value according to ISO 228/1.

To process the obtained results of experiments on the shut-off fittings with disc rotary dampers, we take into consideration their hydraulic resistance (according to the formula:

$$\Delta P = \left(Q/K_{\upsilon}\right)^{2}, \qquad (2)$$

ΔP – pressure loss, bar; Q – estimated flow rate for the flow that passes through the valve, m^3 /h; K_{υ} – conditional throughput with a fully open valve, m^3/h, given in the technical descriptions of manufacturers of pipeline fittings according to ISO 5208:2008. K_{υ} is divided into actual and conditional [20], the calculation formulas are well-known and given in GOST 33257-2015, later transformed into ISO 5208: 2008 (pipeline fittings, control and measurement methods).

Formulas (2), and (3) are well-known in hydromechanics.

Pressure losses in the shutter, which need to be compensated, are taken as:

$$\Delta P = \left(\varsigma \cdot \rho/2\right) \cdot V^{2}, \qquad (3)$$

ζ is the coefficient of resistance of the disc damper, that is, the coefficient of proportionality between the high-speed pressure (calculated by the conditional passage of the fitting) and the pressure drop on this fitting. ζ is a dimensionless coefficient, in the ISO 5208:2008 standard, it is called the coefficient of local resistance and is determined empirically for each type of resistance. V – average flow rate, m/s; ρ – liquid density, kg/m^3.

The resistance factor for the disc damper depends on the following parameters: $\zeta = (2 \cdot \Delta R)/(V^2 \cdot r)$; $\zeta = f(\alpha)$, respectively, according to reference data [4], $\zeta = 0.05$ at $\alpha = 90°$; $\zeta = 32.6$ at $\alpha = 30°$; $\zeta = 3.9$ at $\alpha = 60°$ (α values are indicated according to the scheme in Fig. 1). However, the given values of ζ need to be refined in accordance with the operational parameters.

Using experimental studies, it is necessary to establish a rational zone for the formation of a control signal of the positional pneumatic drive of the shut-off element to enable the angles of rotation of the valve at 40...82 degrees (according to the operational regulations) and refine ζ. The value should be compared with the regulations to enable the required throughput of the disc rotary dampers in the pipeline for a sugar factory. Experimental benches with the following characteristics have been designed for our research. Characteristics of the electrical network, voltage, and power range 24 V DC±10 %. Overload capacity 1.5. Control current 4...20 mA. Control laws of the positioner U/f – sinusoidal. Serial interface RS – 485.

5. Results of experimental verification of the efficiency of shut-off fittings with positional drives

5. 1. Description of the designed experimental bench

The effectiveness of control and operation of shut-off devices, based on technological pipelines in sugar production, was tested on an experimental bench, Fig. 3, and during the introduction of shut-off devices with positional pneumatic drives in sugar production.

In our design of the experimental bench (Fig. 3), it is possible to change the laws of motion of the output link. For example, a disk, a ball, and a valve, which allows the setting and tracking of kinematic and dynamic parameters of shut-off devices under conditions of variable performance for the technological site.

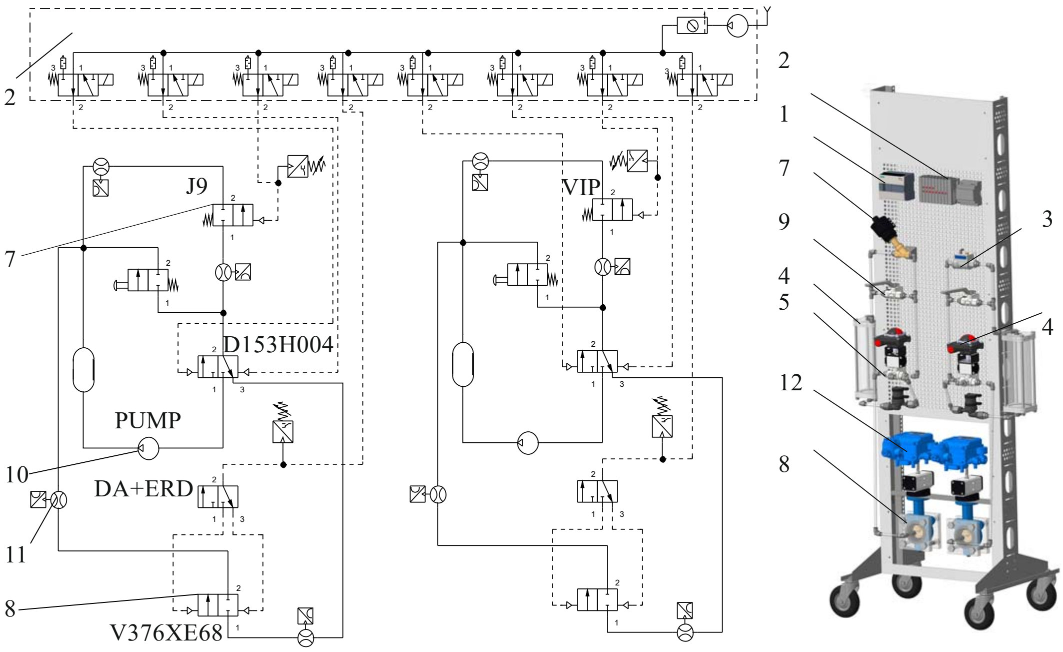


Fig. 3. Diagram of a set-up for studying the effectiveness of the positional pneumatic drive control system for shut-off fittings: 1 – programmable logic controller; 2 – pneumatic island, 3 – coaxial valve VNC –10003; 4 – working receiver for liquid; 5 – ball L-port three-way crane; 6 – terminal switch unit; 7 – control pneumatic actuator; 8 – inter-flange disc damper D-376; 9 – two-way ball valve D-100H004; 10 – pump; 11 – digital flow meter; 12 – electropneumatic positioner (control signal 4...20 mAA)

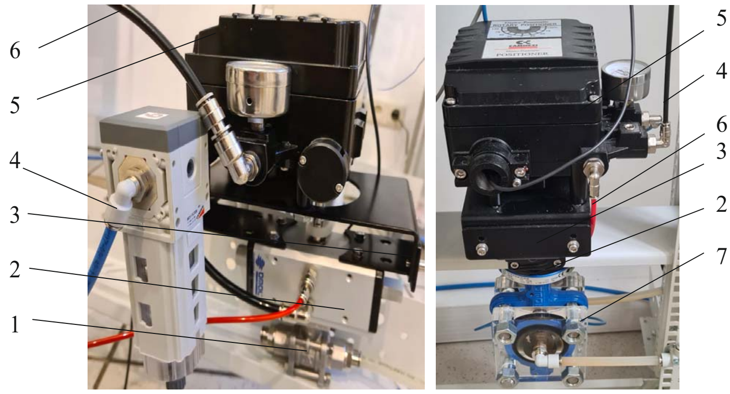
The experimental bench operates in two circuit networks. The high-pressure zone is compressed air (4...8 bar, temperature 20 °C), positions 7–11; the low-pressure zone is water (0.2...3 bar, temperature 20...70 °C, heated by an external thermostat), all other positions. During the experiments, the work of shut-off devices 5, 7, 8 was observed. Digital flow meter 11 and pressure sensors, sensors for the location of the disc damper, ball valve, saddle valve, and digital pressure gauge recorded the parameters of the shut-off devices. Separately, pressure losses were determined in relation to sections from air ducts and water supply pipelines. The pressures were coordinated at the nodal points of the bench with the help of simultaneous adjustment of the signals of the positional pneumatic actuators of the shut-off fittings.

The principle of conducting experimental research on the bench consisted of successive steps. After filling the working receiver by pump 6 with the test fluid, we maintained the operating temperature with a thermostat (20 °C or 40°). The pressure of the pneumatic network was maintained using an air preparation module, a pressure controller (assigning 3×10^5 Pa, 4×10^5 Pa, 5×10^5 Pa, 6×10^5 Pa, 7×10^5 Pa, 8×10^5 Pa). Pressure values were additionally controlled by a digital pressure gauge (0.01×10^5 Pa). The circuit of the low-pressure line is filled with the help of a pump and the indicators of control and measuring devices (flow meters, pressure switches, sensors for the location of shut-off fittings) are recorded. The software of the programmable logic controller sets the parameters of the positional pneumatic actuator and forms the supply of commands to the high-pressure circuit. Shut-off fittings open in the working fluid supply line. Gradually, a signal is set to change the location of the working elements of the shut-off fittings (ball valves, saddle valve, disc inter-flange valves). The drive of the three-way ball valve 3 switches the working fluid supply to the left or right circuit in the pipeline. The cut-off, or regulating shut-off element 8, adjusts the operation for the fluid supply system, or regulates the flow based on the fluid flow meter and compressed air flow meter.

To control the filling of receivers 9, digital flow meters are used. Imitation of a sudden stop to supply fluid can be carried out manually or automatically using a timer. When turning on low pressure (0.2...0.5 bar), the removal of fluid from the pipeline circuit to the receiver begins. The control software (TIA-Portal Siemens) recorded the acquired data on the measured parameters for physical modeling (control signal speed, fluid pressure, fluid flow, air pressure, air flow rate, shut-off element response rate).

Accordingly, Fig. 4 shows the studied positional pneumatic actuator, which was mounted with a ball valve (Fig. 4, *a*) and a disc inter-flange damper (Fig. 4, *b*). The positioner operates on the principle of a nozzle-valve. In the case of an increase in the input electrical signal to the positional pneumatic acts, 4–20 mA, the damper impacts the nozzle. The gap between the nozzle and valve increases. Thus, as a result, pressure arises on the working spool, and its forward movement begins, which enables the discharge of compressed air to the drive.

When the pressure in the working chamber of the drive begins to increase, the shaft (rod) of the drive will move, and there will be pressure on the cam, which enables the tension of the resistance spring. The spring force has to be compensated by the torque on the electromagnetic motor, which will further enable the return of the damper to its original position. The gap with the nozzle will decrease, the pressure level will decrease, and the spool will move to the specified location. After stopping the drive, the entire positioner control system returns to its original position.



a *b*

Fig. 4. General view of the experimental control system for the positional drive of shut-off fittings: *a* — ball valve drive; *b* — disc damper drive; 1 — ball valve; 2 — pneumatic rotary drive; 3 — mounting flange; 4 — pipeline for air supply with air preparation unit; 5 — control module-positioner; 6 — pipeline for air removal to the pneumatic actuator; 7 — rotary inter-flange disc damper

During the operation of the pipeline fittings, the interaction of the flow of the working medium with the elements of the flow part of the fitting inevitably arises. Accordingly, the results of such an interaction may be the occurrence of vibration of the body of the elements, pressure drops, noise, changes in speed characteristics for the flow of the working medium, and temperature changes. Therefore, studies on the hydrodynamics of the flow of the working medium were carried out under different technological operating modes to examine the efficiency of the pipeline system and equipment associated with the elements of shut-off fittings.

5. 2. Mathematical modeling of control over shut-off devices with subsequent analysis of individual stages

Fig. 5 shows the constructed scheme of the positional pneumatic subsystem for regulating the flow characteristics of pipelines with Newtonian liquid. The designed scheme of the control system consists of an electrical signal mismatch meter (Σ), an electronic error signal amplifier (EPS), a pneumatic amplifier (PP), an electromechanical transducer (EMF), an actuator pneumatic cylinder (PC). Also, the system has a pressure sensor at the pipeline with a pneumatic positioner (OP), a feedback sensor for the movement of the piston of the pneumatic cylinder, and a feedback sensor of the volumetric flow rate (DT). The object of control selected is a disk, a ball, or a shut-off plunger for shut-off fittings (OR).

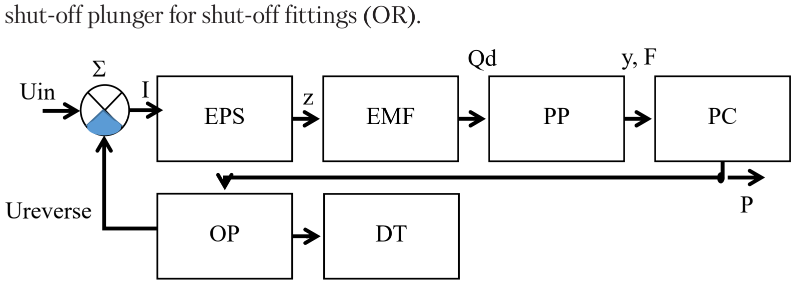


Fig. 5. Generalized block diagram of the control object (shut-off device): (Σ) — electrical signal mismatch meter, electronic (EPS) error signal amplifier, (PP) — pneumatic amplifier, (EMF) — electromechanical transducer, (PC) actuator pneumatic cylinder, (OP) — pressure sensor in a pipeline with a pneumatic positioner, (DT) — feedback sensor for the movement of the pneumatic cylinder piston, a volumetric flow feedback sensor; (OP) — control object (disc, ball, shut-off plunger)

The built mathematical model simulates the transients of the pressure control subsystem in the pipeline. The model includes the function of changing the area for the critical cross-section of the hole depending on the movement of the working body of the shut-off element, $F^*f=(y)$. The modeling task to study the work of the control pilot valve of the positioner is fulfilled. Modeling of transients in the pneumatic subsystem of regulation of shut-off fittings is justified by assumptions.

As a force element of the drive, a double-sided pneumatic cylinder of rotary action was chosen; the flow rates and pressure recovery in the pneumatic booster, the power supply and discharge pressures are constant values. As for the temperature, viscosity of the test fluid in the pipeline, the parameters do not change during the studied dynamic process. Volumetric losses in the supply pneumatic lines of the pneumatic cylinder are insignificant, we can neglect them. According to the accepted assumptions, the conclusions of works [2, 14], and the description of the correspondingly derived mathematical model of the positioner' work, we obtain the equation:

Equations for the electrical circuit of an electromechanic converter in a pneumatic positioner (Fig. 6):

$$U_{dr}=R_{dr}\cdot i_{dr}(t)+L_{dr}\cdot\frac{di_{dr}}{dt}+K_{\mathrm{Cr\,eds}}\cdot\frac{dh(t)}{dt}, \tag{4}$$

U_{dr} is the voltage in the winding of the electromagnet control (that is, the value of the control voltage of the drive of the shut-off element, namely, the disc damper), V; R_{dr} – active resistance of the control winding of the electromagnet, Ohm; i_{dr} – current strength in the control winding of the electromagnet coil to the positioner of the disc damper (control signal), A; $L_{dr}\cdot\frac{di_{dr}}{dt}$ – the value of EMF of self-induction, proportional to the rate of change in the power of (alternating) current, V; $K_{\mathrm{Cr\,eds}}\cdot\frac{dh(t)}{dt}$ – anti-EMF for the electrical circuit of the electromechanical converter, V.

Description of the equation of motion of the control valve for the shut-off valve:

$$m_{dr}\cdot\frac{d^2h(t)}{dt^2}=K_{fid}\cdot i_{dr}(t)-b_{vdr}\cdot\frac{dh(t)}{dt}-c_{dr}\cdot h(t), \tag{5}$$

m_{dr} is the mass of the control valve for the throttle, kg; K_{fid} – current strength coefficient of an electrical circuit for an electromechanical converter, N/A; b_{vdr} – coefficient of viscous friction in throttles, N·s/m; s_{dr} – coefficient of spring stiffness in throttles, N/m.

Description of the equation of motion of the valve spool during a constant pressure drop:

$$m_K\cdot\frac{d^2x_K(t)}{dt^2}=A_1\cdot\left(p_2(t)-p_3\right)-$$
$$-b_{VK}\cdot\frac{dx_K(t)}{dt}-c_K\cdot x_K(t), \tag{6}$$

m_K is the mass of the valve spool for constant pressure drop, kg; A_1 – area for the end surface of the valve of a constant pressure drop, m^2; $x_k(t)$ – the dependence of the movement of the valve spool for a constant pressure drop on time, m; p_3 – the dependence of the pressure at the outlet of the throttles on time, Pa; c_K – the coefficient for spring stiffness in the valve of constant pressure drop, N/m; b_{VK} – coefficient of viscous friction of the spool in the valve for a constant pressure drop, N·s/m.

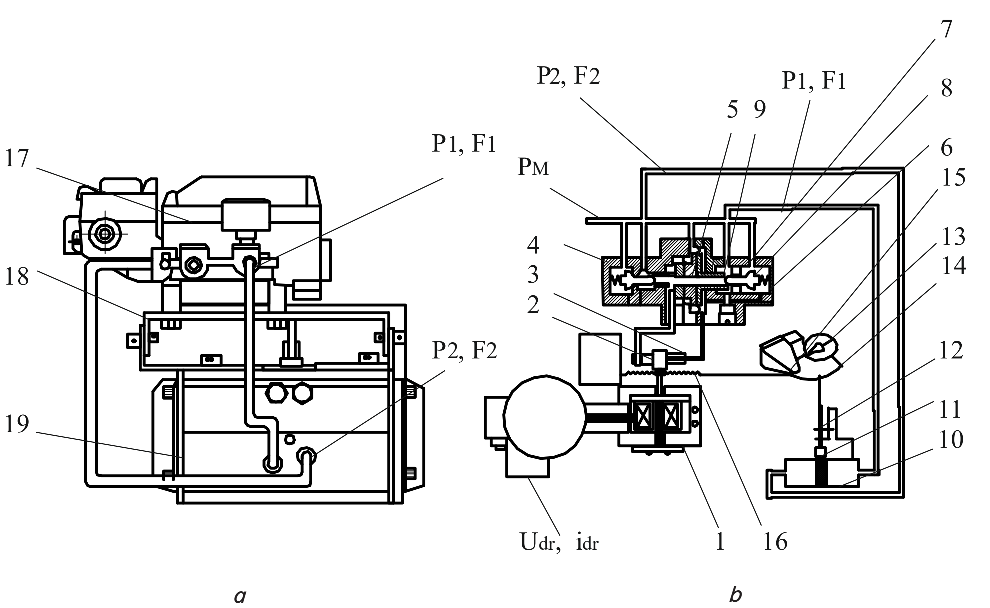


Fig. 6. Estimation scheme of the pneumatic position drive: a) the basis is a rotary pneumatic actuator of two-way action; b) a device for a positioner with a pilot valve: 1 — electromagnetic control device (i/p — DC signal transducer to proportionally alternating supply pressure); 2 — valve for the throttling device; 3 — working nozzle; 4 — left-side working chamber; 5 — working spool; 6 — right-side working chamber; 7 — saddle; 8 — spool piston; 9 — main pipeline; 10 — rotary drive (with pneumatic cylinder); 11 — link; 12 — drive shaft; 13 — mechanical sensor of the initial location of the disc damper; 14 — cam; 15 — starting spring; 16 — working spring; 17 — control module housing; 18 — mounting bracket; 19 — rotary pneumatic cylinder, P_1, P_2 — pressure of the supply and discharge line of the control pneumatic distributor; F_1, F_2 — cross-sectional area of the supply and discharge line of the control pneumatic distributor, P_M — pressure of the compressed air supply network

Description of the equation for the balance of airflow through the positioner loss controller:

$$\mu_K \cdot b_K \cdot x_K(t)\cdot\sqrt{\frac{2\cdot\left(p_1(t)-p_2(t)\right)}{\rho_0}}-$$
$$-\mu_{dr}\cdot b_{dr}\cdot h(t)\cdot\sqrt{\frac{2\cdot\left(p_2(t)-p_3(t)\right)}{\rho_0}}=\ldots \quad (7)$$
$$\ldots=\frac{V_{K1}}{2E}\cdot\frac{dp_2(t)}{dt}+A_1\cdot\frac{dx_K(t)}{dt},$$

μ_K is the flow factor for the throttling slot of the constant pressure drop valve; E – reduced modulus of volumetric elasticity for the working fluid, Pa; μ_{dr} – flow rate factors for the throttle; b_K – width of the valve spool slot for a constant pressure drop, m; V_{K1} – the volume of the upper cavity for the valve of constant pressure drop, m^3; b_{dr} – width of the throttle gap, m; V_{K2} – the volume of the working lower cavity for the valve of constant pressure drop, m^3.

The shut-off device being operated is subjected to control and disturbing effects, from which changes in the state of the system occur over time. Under actual conditions, the effects on the system of the shut-off device are sometimes random, and this causes random and stochastic (respectively indefinite) processes in the system.

The nature of random effects on a system with a pneumatic drive is usually extremely limited in the actual process, therefore, during the studies of the dynamic properties of the system, the so-called deterministic effects were applied. Typical deterministic influences define three types of influences: stepwise, harmonic, and impulse.

During the harmonic impact, the behavior of the system in the frequency domain of the signals was considered. Then, quite effectively, it is possible to solve the problems of system stability and also to investigate the influence of various factors on the dynamic characteristics for individual elements and the system as a whole [1, 6, 9].

To regulate the flows for the working technological environment, which is a Newtonian liquid, positional pneumatic actuators were used in the experimental benches. The control signal i_{dr} was a serial asynchronous interface that provided information transmission under the start-stop mode of 4–20 mA by direct current. During the research, an offset range was formed, that is, the smallest signal value (for example, 0) corresponded to a current of 4 mA, the largest — 20 mA. The entire range of permissible values occupied 16 mA. Zero current value in the circuit indicated the diagnosis of an emergency, interruption of the control signal to the shut-off device.

The main element of the positioning of the positional type of drives chosen was the nozzle-valve system. The control system reacts, on the one hand, on the magnetic field from the electric coil of the control circuit with the pneumatic drive, and on the other hand, the mechanical connection with the output link in the drive. This control approach provides a proportional change in the location of the output link depending on the change in the control signal.

5. 3. Analysis of individual stages of operation of shut-off fittings based on accepted assumptions

On the bench, separate stages of the disk rotary inter-flange damper were experimentally modeled. Thus, under the opening modes at a given angle (30°, 60°, 90°), holding in the set position, and completely closing, the flow rate characteristics of the working environment were recorded by the digital flow meter. The simulated modes of operation of the positioner with specified control signals for the expected operation of the shut-off fittings were investigated. In order to form a control signal for a shut-off device with an electro-pneumatic positional drive, changes in current load in the range of 4–20 mA were taken into consideration, namely:

– a control signal with values of 4.0 mA-8.81 mA-4.0 мA is set for opening-holding-closing the disc of the shut-off device at 30° (Fig. 6, *a*);

– a control signal with values of 4.0 mA-13.61 mA-4.0 мA is set for opening-holding-closing the disc at 60° (Fig. 6, *b*);

– a control signal with values of 4.0 mA-20.00 mA-4.0 мA is set for opening-holding-closing the disc at 90° (Fig. 6, *c*).

With the help of a digital control and measuring system and Siemens Software TIA Portal V15 – PLC, the indicators of flow characteristics and pressure changes in the positional pneumatic drive were recorded in real time. The results are shown in Fig. 7, for the opening angles of the disc damper of 30°, 60°, and 90° – according to the variable value of the control signal relative to the pressure (1...4 bar), and the sampling of measuring indicators for the control system in real time (100 measurements per 1 s). Mathematical and statistical treatment, according to the procedure from [7], showed an error in measuring standard values for flow rate levels of ±7.011 % with a confidence probability of 0.95. The vertical axis of the plots in Fig. 7, *a–f* is common to the pressure in the stream and to the flow rate.

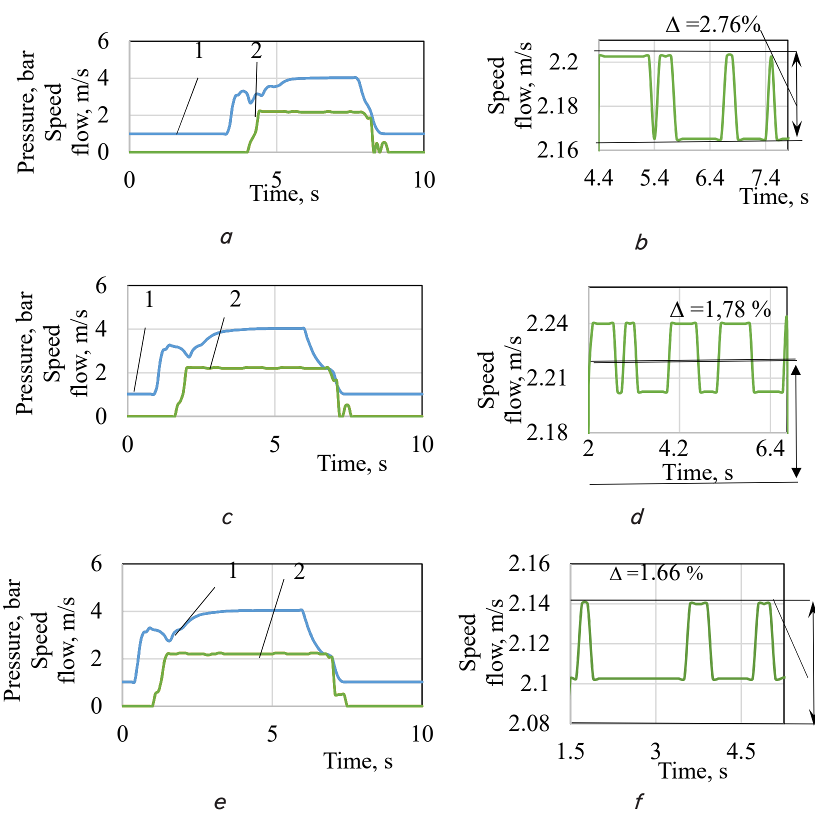


Fig. 7. Generalized results of studying the effectiveness of the control signal of the pneumatic positional drive to the throughput of the rotary valves DN, with the conditions of opening – holding – closing at an angle: *a, c, e* – the dependence of pressure and flow rate on the time of operation of the valve, respectively, for the angle of rotation 30°; 60°; 90°; *b, d, f* – deviation of the control signal and flow rate, respectively, for the angle of rotation 30°; 60°; 90°; 1 – control pressure, 2 – flow rate, Δ – hysteresis of the measured value, %

5. 4. Full-scale studies of the flow rate characteristics of shut-off devices

Our full-scale experiment took into consideration the conditional throughput of the rotary dampers, the angle of rotation of the disk with the control of the positional drive, and the level of juice in the housings of the evaporative station.

Measurements were carried out at the section of the stabilizing circuit in the reduction-cooling plant, in order to study the results of using the introduced ball valve with a V-shaped cutout and a positional pneumatic drive (Fig. 8). A ball valve with a rated passage of 32.0 millimeters with a pass-through V-shaped cutout at 60° was used at the sugar mill. Such controlled shut-off fittings (valve) are used for metered water supply to reduce the temperature of steam after a working turbine.

Fig. 8, *a*, *b* illustrates the data of the site's work on steam cooling after feeding to the evaporative station. Change in temperature level in accordance with prior and after cooling and the angle of rotation for the ball. Processing of numerical values demonstrates the recorded performance indicators, namely: the average value of the angle of rotation for the ball is 17.61 degrees. Regarding the average value of the vapor temperature after cooling, it is 130.91 °C during a given value of 130.0 °C (with a deviation of 0.71 %). Summing up, we note that a satisfactory result was obtained, with a small average value of the angle of rotation of the ball. That is, it would be more effective to use a ball valve for a smaller size, or with a smaller angle of segment cutout. Regarding the effectiveness of the control system of the positional pneumatic actuator of the shut-off valve, satisfactory results were obtained.

Fig. 9 shows the process of maintaining the juice level in the circuits between the first and second housings of the evaporative station using the DN rotary inter-flange damper.

Our results demonstrate the effectiveness of the positional drive control system of the disk rotary inter-flange damper, depending on the norms for adjusting the level of juice in the working enclosures. We have investigated the actual values for the juice level in the first and second housings, the performance characteristics for the evaporative station, compliance with the specified values of juice levels, a change in the angle of rotation of the working disc of the damper. According to the results of processing numerical values, the following indicators were obtained: the average value for the angle of rotation of the disc damper is 43.0 degrees. That is, owing to the control system, the optimal control zone is effectively provided, determined during the research work involving the experimental bench.

The average value for the juice level in the first housing was 65.861 % of the specified level with a value of 66.0 %. The average value for the juice level in the second housing was 84.76 % with a given value of 86.0 %. Our results satisfy the existing requirements for the technical regulations at a modern sugar enterprise.

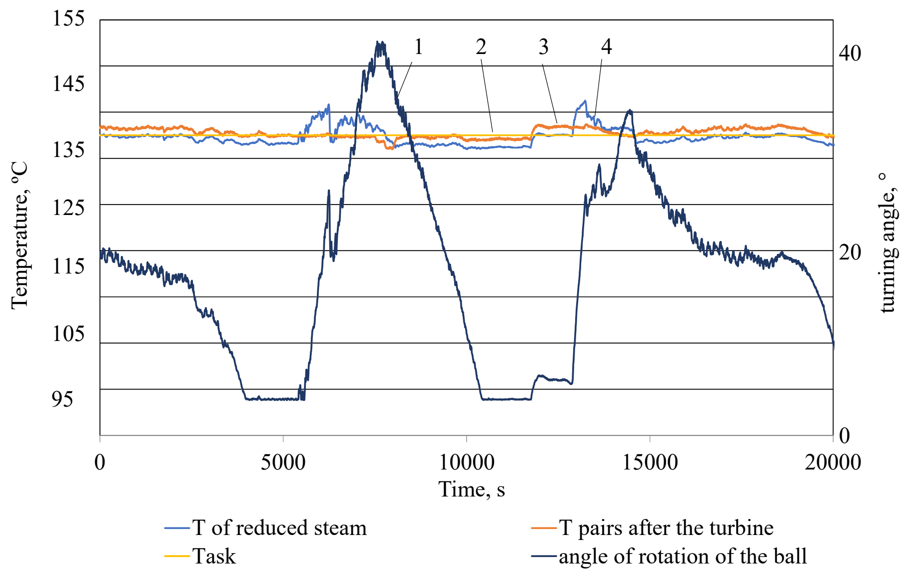
The links between the hydraulic and electrical characteristics of the disc damper with the parameters of the working medium (sugar juice) are obtained and are given in Table 1.

The values of hydraulic and electrical characteristics given in Table 1 prove that during the use of pneumatic positional drives, the smooth operation of the shut-off elements of the pipeline fittings is achieved by adjusting the control signal over the current. Our results in Table 1 are the basis for solving the problem of correcting the regulation of steam temperature by the metered supply of cold water to the general steam supply system in front of the evaporative station (Fig. 8).

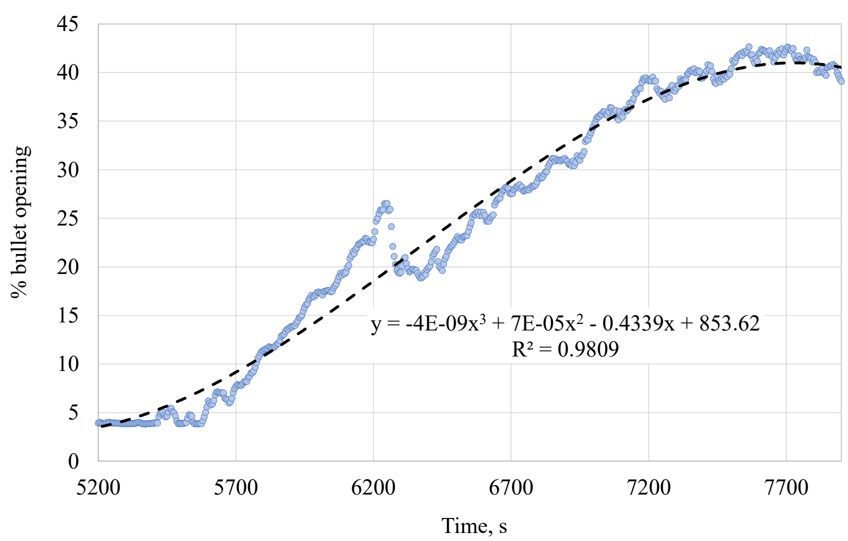
Table 1

The effect of changing the control signal I on K_v, depending on the hydraulic head ΔP and the rated size of the disc damper DN 40 (diameter of the passage hole, 40 mm)

–	I	ΔP=4, bar	ΔP=2, bar	ΔP=0.4, bar	ΔP=0, bar
α, °	mA	K_v, m^3\h	K_v, m^3\h	K_v, m^3\h	K_v, m^3\h
1	3	2	4	5	6
0	4	0	0	0	0
10	5.78	1	1	1	0
20	7.56	2	1	1	0
30	9.33	4	2	2	1
40	11.11	12	6	5	1
50	12.89	26	19	9	2
60	14.67	62	37	20	9
70	16.44	80	74	37	19
80	18.22	81	81	47	26
90	I	82	82	51	29

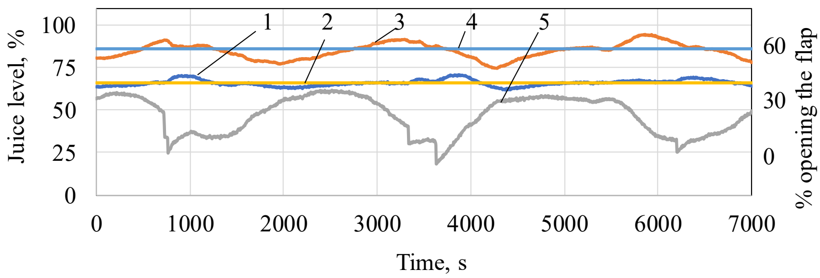


a

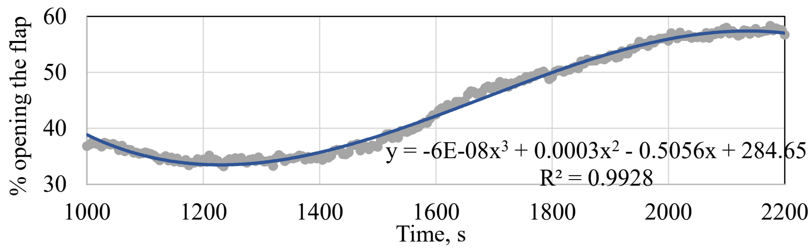


b

Fig. 8. Generalized characteristics of changes in steam temperature in the stabilization working circuit of a reduction-cooling unit when using a ball valve controlled by a positional pneumatic drive with a V-neck to regulate water supply: *a* – generalized characteristic of changes in temperature indicators from the angle of rotation of the ball: 1 – angle of rotation for the ball, 2 – technological task; 3 – temperature for steam after the turbine; 4 – temperature for reduced steam; *b* – angle of rotation for the ball



a



b

Fig. 9. General demonstration of adjusting the juice level in the first and second housings of the evaporative station by a disc damper with a positional pneumatic drive: *a* — a diagram of the values of the juice level in the first and second housings, as well as the angle of rotation of the disc damper: 1 — the level in the first housing; 2 — technological task 1; 3 — levels in the second housing; 4 — technological task 2; 5 — the angle of rotation of the working valve; *b* — the results of mathematical and statistical processing, generalized characteristics of the angle of rotation of the damper

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

The changes in the flow rates of the working environment depending on the angle of rotation of the working damper (Fig. 1) have been established and the rational zone of influence is taken into consideration according to the control signal of 4–20 mA. During the studies, the characteristics of the throughput control measurement for rotary dampers DN (Fig. 2) depending on the angle of rotation of the disk are taken into consideration. We have designed the experimental bench (Fig. 3) and obtained the results of the study of the effectiveness of the control system for the position drive of the elements of shut-off fitting. The change in the laws of motion of the output link (disk, ball, valve) is analyzed, which provides tracking of the kinematic and dynamic parameters of shut-off devices under the conditions of variable performance for the technological section. The influence of hydraulic resistance on the operation of shut-off elemens based on dependences (2), (3) is taken into consideration.

The conducted simulation of a sudden stop for the supply of fluid can be carried out manually or automatically using a timer. When turning on the low pressure (0.20...0.50 bar), the fluid is discharged from the pipeline circuit to the receiver. The control program (TIA-Portal Siemens) recorded our results of the measured parameters for physical modeling (control signal speed, air pressure, air flow, fluid pressure, fluid flow rate, shut-off element response rate).

During the study at the experimental bench, we tested the scheme of the control system consisting of an electrical signal meter of inconsistency, an electronic amplifier of the error signal, a pneumatic amplifier, an electromechanical converter, and a pneumatic cylinder. In order to study the efficiency of the shut-off elements, Camozzi digital control and measuring systems were tested: a pressure sensor in the pipeline with a pneumatic positioner, a feedback sensor for the movement of the pneumatic cylinder piston, and a volumetric flow feedback sensor.

It was confirmed that the shut-off device, under operating conditions, is subjected to control and disturbing effects. And it is the efficiency of the control system that changes in the state of the technological system over time depend. It has been established that under real conditions, the impacts on the system of the shut-off device are sometimes random, and this causes random and stochastic processes in the system.

It is worth noting the following limitations regarding the study of the effectiveness of the control system of the positional pneumatic actuator of shut-off fittings. During the experiment with the disk rotary damper under different modes, the operating modes of the positioner with the specified control signals for the operation of the shut-off fittings were simulated. The formation of the control signal for the shut-off device, with a pneumatic positional drive, was a change in the current load by the ranges: for opening-holding-closing-closing the disc of the shut-off device at 30° with values of 4.0 mA-8.81 mA-4.0 mA; for opening-holding-closing the disk at 60° with values of 4.0 mA-13.61 mA-4.0 mA; for opening-holding-closing the disk at 90° with values of 4.0 mA-20.0 mA-4.0 mA. The nature of random effects on a system with a pneumatic drive is usually extremely limited in the actual process, therefore, during the studies of the dynamic properties of the system, the so-called deterministic effects were applied. Accordingly, the deterministic effects are three types of influences: stepwise, harmonic, and impulse. During the harmonic impact, the behavior of the system in the frequency domain of the signals was investigated.

The results of experimental studies (Fig. 7) prove the effectiveness of solving problems of system stability, and also substantiate the influence of various factors on the dynamic characteristics for individual elements and the system as a whole. According to the study of various modes of operation of shut-off devices – the obtained values of amplitude pressure fluctuations, at the time of opening the valves are 3.8...7.21 % higher than at the time of closing.

In contrast to [16] where the study of the flow rates of the working environment was justified only by a system of flow meters and control valves, the influence of the position drive control system on the entire technological process was analyzed. The result of our full-scale studies of the flow rate characteristics of shut-off devices (Fig. 8) makes it possible to influence the change in the temperature level prior and after cooling the steam after feeding to the evaporative station. Processing the numerical values of the angle of rotation for the ball demonstrates the recorded performance indicators within 130.91 °C for a given value of 130.0 °C (with a deviation of 0.7 %). This becomes possible owing to the mathematical model built and implemented in the control system for the positioner operation, given by equations (4) to (7). We simulated transients of the pressure control subsystem in the pipeline. Equation (7) takes into consideration the function of changing the area for the critical cross-section of the hole depending on the movement of the working body of the shut-off element, $F^*=f(y)$.

The processing of the numerical values of the conducted field experiments demonstrated the following indicators: the average value for the angle of rotation of the disc inter-flange damper is 43.0 degrees. That is, the compliance with the optimal regulation zone, which was determined during the research work at our experimental bench, was confirmed. Experimentally, the effectiveness of the positional pneumatic drive control system of shut-off fittings has been proven. Namely, adjusting the level of juice in the first and second housings of the evaporative station with a disc damper with a positional pneumatic drive. Thus, the average value of the juice level in the first case is 65.86 % with a given value of 66.0 %; the average value for the juice level in the second case is 84.76 %, provided that the level is 86 %.

The results of the experimental study of the work of the steam cooling area after feeding to the evaporative station (Fig. 8) and the efficiency of the positional drive control system of the disc rotary inter-flange damper were established (Fig. 9). A satisfactory result was obtained within an error of 0.51 % for the angle of rotation of the disc inter-flange damper, the response time is justified. A drawback in practical expectations for the use of the results of our research (Fig. 7, 8) is a warning against a sharp increase or decrease in the pressure of the fluid that moves with a sudden change in flow rate. This disadvantage is associated with the phenomena of water hammer, caused by the extremely rapid overlap of the pipeline section during the operation of industrial pipeline fittings. This can lead to damage to pipelines, depressurization of systems, failure of instrumentation and controls.

Further research is planned to be expanded in order to analyze the control processes and the efficiency of other types of shut-off fittings, to study the safety of shut-off fittings from the effects of hydraulic impacts.

7. Conclusions

1. We have designed and tested the experimental bench to study the effectiveness of the positional drive control system of shut-off fittings. The experimental bench is designed in a two-circuit network. The first circuit – the high-pressure zone – to control compressed air. The second circuit – the low-pressure zone – to control the test liquid. In our structure of the experimental bench, it is possible to change the laws of motion of the output link (disk, ball, valve). This enables the setting and tracking of kinematic and dynamic parameters of shut-off devices under conditions of variable performance for the technological site.

The design of the experimental bench provides for determining pressure losses in the sections of the air ducts and the fluid supply pipeline, and software-controlled pressure coordination for the nodal points of the bench during the adjustment of the signals of the pneumatic positional drive, which enables the optimal law of motion.

The operating modes of the disc damper and ball valve, based on proportional elements with feedback (4–20 mA), have been programmatically established and investigated.

2. An analytical description of the mathematical model of control of shut-off devices on the example of a disk rotary damper with subsequent analysis of individual stages and accepted assumptions has been developed. The scheme of the positional pneumatic subsystem by regulating the flow characteristics of pipelines with Newtonian liquid has been worked out. The study of positional control modules of shut-off devices was performed. The working signal for controlling the disc damper using a pneumatic positioner with a serial asynchronous interface for transmitting information in the start-stop mode of 4–20 mA by direct current is substantiated. The offset operating range of the control signal is described: the smallest signal value 0 corresponded to a current of 4 mA, the largest – 20 mA. The range of permissible values was 16 mA. Zero current value in the circuit diagnosed an emergency situation of interruption of the control signal to the shut-off device the current value in the circuit diagnosed an emergency situation of interrupting the control signal to the shut-off device.

3. Individual stages of operation of the synthesized shut-off fittings on the basis of accepted assumptions have been analyzed. Measurements were carried out for the opening angles of the disc damper of 30°, 60°, 90° – according to the variable value of the control signal relative to pressure (1...4 bar), and the sampling of measuring indicators for the control system in real time (100 measurements per 1 s). According to the result of mathematical and statistical processing, the error of measuring the standard values for flow rates is ±7.01 % with a confidence probability of 0.95. Our experimental results confirmed the adequacy of the numerical modeling regarding the study of the operation of the disk rotary inter-flange damper, as well as the previous assumptions in the mathematical model. The speed of the working medium in the flow part of the shut-off device has a characteristic decrease in the initial cross-section (during the formation of the angle of rotation of 90° for the disc damper). Accordingly, the absolute values for pressure pulsations in the flow section are reduced.

4. An experimental study was carried out at a sugar factory in order to test the efficiency of the controlled shut-off fittings.

The results of the steam cooling area after feeding to the evaporative station were obtained and analyzed. The changes in temperature level prior and after cooling and the angle of rotation for the ball were recorded. We obtained the average value of the angle of rotation for the ball of 17.6 degrees; the average value of the steam temperature after cooling is 130.91 °C (subject to a given value of 130.0 °C). The deviation of the set value is 0.7 %. Owing to the effective control system of the positional pneumatic drive of the shut-off device, a satisfactory result was obtained with a small average value of the angle of rotation of the ball. The characteristic for changing the temperature of steam in the network of the stabilization circuit of the reduction-cooling unit using a ball valve (with a V-neck), for an adjustable water supply, was established.

The results of the effectiveness of the use of the positional pneumatic drive control system of the disc rotary inter-flange damper, depending on the regulated norms for adjusting the juice level in the working enclosures, were established. According to the results of the experiment, the obtained indicators are the average value for the angle of rotation of the disc damper of 43.0°. The average value for the juice level in the first housing was 65.86 % in compliance with the specified value of 66.0 % (the deviation was 0.21 %). The average value of the juice level for the second housing was 84.76 % with a given value of 86.0 % (the deviation was 1.451 %).

According to the research results, an error of 0.51 % was established for the angle of rotation of the disc inter-flange damper and the response time of the control system was determined – 0.02 s.

Our results confirmed the effectiveness of adjusting the flow rates of the working environment according to the specified characteristics, subject to the use of a positional pneumatic drive. The findings fully meet the requirements of the technological regulations for controlled shut-off fittings.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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