UDK 004.9:681.51:51-74

Olena S. Nazarova[1], Candidate of Technical Sciences, Associate Professor of Electric Drive and Automation of Industrial Plants Department, E-mail: nazarova16@gmail.com, Scopus ID: 56826084800, ORCID: http://orcid.org/ 0000-0002-0784-7621
Irina A. Meleshko[1], PhD Student of Electric Drive and Automation of Industrial Plants Department
E-mail:iameleshko@gmail.com, ORCID: http://orcid.org/ 0000-0003-2473-5434
[1]National University "Zaporizhzhia Polytechnic", Zhukovskogo Street, 64, Zaporizhzhia, Ukraine, 69063

EXPERIMENTAL RESEARCH AND COMPUTER MODELING OF THE OBSTRUCTION OCCURRENCE IN THE PNEUMATIC CONVEYING SYSTEMS PECULIARITIES

Annotation. *At designing new and modernizing existing pneumatic transport systems it is necessary to take into account changes in the electromechanical parameters of the equipment during start-up or other transient conditions that are most dangerous from the point of view of the occurrence of a blockage in the pneumatic system. Given the high cost of electricity and large volumes of production during the transportation of bulk materials, the urgent task is to reduce the specific consumption of compressed air during transportation, taking into account the development of automatic control systems for the main factors, namely, pressure loss at the outlet of the pneumatic system, affecting the occurrence of blockages of pneumatic conveying systems. The aim of the work is to conduct experimental studies and computer modeling of the features of blockage in pneumatic conveying systems during transportation of bulk materials associated with pressure loss at the outlet of the pneumatic transport systems. This goal is achieved by conducting experiments, on the basis of which an analytical expression is obtained to determine the speed of the mixture, which provides the minimum admissible pressure at the outlet of the air bag by the technological process. An analytical dependence of the occurrence of a possible clogging point on the pressure drop at the outlet of the air duct is obtained, which determines the minimum step of the impact on the transported two-phase flow in order to prevent the occurrence of blockages, and also, if necessary, indicates the place of occurrence of the blockage. It was established that with increasing pressure difference at the inlet and outlet of the pipeline, the point of possible blockage shifts towards the chamber feeder. Stabilization of the humidity of the compressed air supplied to the pneumatic line through the use of more sensitive and faster measuring equipment and automated control means will reduce the possibility of blockage, save energy, and therefore increase the efficiency of the pneumatic conveying system. Mathematical and computer models of the electric drive of the pneumatic transport system have been developed; graphs of electromechanical processes have been obtained, confirming its adequacy with an accuracy of ten-twelve percent for steady regime. Using these models will save time and money on conducting preliminary experiments in the development of new and modernization of existing pneumatic transport systems.*

Keywords*: computer modeling; pneumatic conveying system; pneumatic transport system; bulk materials; compressed air; energy efficiency*

Introduction. The pneumatic method of transporting bulk materials is also widely spread at enterprises in the metallurgical, mining, energy, chemical, pharmaceutical industries, in the agricultural sector and in construction [1-2]. Pipeline transport accounts for 30% of all industrial transport systems, which determines the relevance of the subject under consideration. The development of technologies for the transportation of bulk materials is aimed at reducing the unit cost of transporting one ton of bulk material by reducing the consumption of electric energy during transportation; works with the minimum allowable pressure in the air duct, allowing you to choose an electric motor of lower power, which with such production volumes gives a significant economic effect [3].

The disadvantage of pneumatic conveying systems (PTS) is the probability of delay in the reaction of the automatic control system (ACS) to pressure changes and, as a result, blockages of the pipeline with bulk material, which causes the process to stop, simple equipment and significant material losses [4].

The reasons of blockages include an unstable mode of transportation, a decrease in pressure at the outlet of the pneumatic transport system. The process of the appearance of gallows is explained by a decrease in the distance between particles with an increase in the concentration of the solid phase [5-6]. As a result, these particles fall into the hydrodynamic trail of the particles flying in front, while the frontal resistance decreases, the speed increases, and, as a consequence, the particles fall out of the flow [7-8].
Among the methods to prevent the formation of blockages in pneumatic conveying systems, the following are known: constant control of pressure throughout the pneumatic conveying line [9]; increase in pressure in the pneumatic route, which entails an increase in electricity consumption [10-11]. To prevent such undesirable phenomena, it is necessary to take a survey of the electromechanical processes of pneumatic conveying of bulk materials, pay attention to the selection of the most advantageous of them and investigate the stability of their condition, which is an urgent task in the design and operation of pneumatic conveying installations [13-14], taking into account the dependence on the length of the air duct [15], on the selected operating speed of the transporting

stream [16]. A significant disadvantage of pneumatic transport is also its vulnerability of sudden power outage [17]. In such a situation, the transported bulk material lies in the air duct, while blockages and plugs are possible, which seriously complicates the restoration of the operational state of the route. The energy intensity of the transportation process with the pneumatic method of moving bulk materials, the design features of pipelines [18-19] and the accessory equipment, technical parameters of pneumatic conveying systems largely depend on the modes of movement of bulk materials, the possibility of automating the processes of their transportation [20]. The specific energy consumption and wear of the pipeline determines its effectiveness and depends on the mode of transportation used. Optimization of the electromechanical processes of moving bulk materials, as well as the creation of energy-saving methods of pneumatic transport operating in its unstable modes, is an urgent task.

The aim of the work is to conduct experimental studies and computer simulations of the occurrence of blockages in pneumatic conveying systems during transportation of bulk materials, accompanied by pressure loss at the outlet of the PTS, increasing the humidity of the compressed air supplied to the system and obtaining an analytical dependence of the probable point blockages in the pipeline.

Methods, results and discuss

Determination of the operating modes of pneumatic transport installations, in which the transfer of 1 ton of alumina with a minimum air flow rate and a minimum probability of occurrence of blockage significantly increases their efficiency.

Table 1 shows the results of an experimental study of the formation of walls at different costs of compressed air, the pressure dynamics in the PTS certain information and the of the mixture density are determined for the transfer of 1 ton of Al_2O_3 [21].

During the experiment, measuring instruments were used: Honeywell STG700 pressure sensor, providing accuracy within the range of 0,05 % of the measurement range; pressure sensor Sapphire 22 DD 2430 for measuring air flow with an accuracy class of 0,5%; weight alumina in front of the chamber feeder was determined by VKD-3T-DA scales, accuracy class III is average. The experiment was to move 1 ton of Al_2O_3 alumina from the chamber feeder to the collection hopper at a distance of 370 m. Initially, 90 м^3 of compressed air was used to transfer 1 ton of Al_2O_3, while the pressure P_1 at the inlet of the test section was $6.76 \cdot 10^5$ Pa. and at the output, $P_2 = 6.12 \cdot 10^5$ Pa. In this case, there is practically no pressure drop and the density of the transported mixture is 38.1 kg / м^3. As the air volume for transportation decreases, an increase in the pressure drop at the end point of the air duct and an increase in the density of the transported medium are observed. With an air volume of 35 м^3, the experiment was terminated due to the lack of movement of the mixture. This volume is not enough to aerate alumina to a density of movement. It was experimentally established that the optimal displacement volume is a value of 60 ± 5 м^3.

Table 1 Dependence of compressed air consumption (V, m^3), line pressures (P_1 and P_2, 10^5, Pa) and the density of the mixture being transported (ρ *sum*, kg / m^3) at transfer of 1 ton Al_2O_3

V, m^3	P_1,, 10^5, Pa	P_2,, 10^5, Pa	ρ *sum.*, kg/m^3
90	6.76	6.12	38.1
85	6.43	5.76	44.45
80	6.14	5.38	50.8
75	5.79	4.98	57.15
70	5.52	4.56	63.5
65	5.24	4.15	69.85
60	4.91	3.74	76.2
55	4.59	3.32	82.55
50	4.28	2.99	95.25
45	4.03	2.56	101.6
40	3.64	2.03	107.95
35	1.97	0	0
30	0	0	0

At the same time, the operation of the pneumatic transport system is relatively stable and the cost of compressed air for transportation is most effective

Thus, a decrease in pressure at the outlet of pneumatic conveying systems reduces the energy efficiency of the system as a whole, and can also lead to blockages.

In order to study the change in pressure in the pneumatic transmission line, a passive physical experiment (under the normal functioning of the facility) was conducted at JSC: “Zaporizhzhya Production Aluminum Combine”, where the object of the study was a part of the pneumatic circulation (Fig. 1) from the chamber feeder (CF) to the receiving hopper (RH) of the electrolysis workshop.

Figure 1 shows the loading of alumina from the refrigerator of a calcination furnace (RCF) through an opening in a chamber feeder (CF). By turning the compressed air supply valve from the central manifold, the flow of material into the transport line is regulated, controlled by this is the pressure on the manometer (P1), the discharge pressure from the compressed air manifold (CA) and the flow rate of alumina (Al_2O_3). The damper (Z) controls the flow of the mixture into the pneumatic transport line. The compressed air supply is controlled by a drive motor (СТД-1600-2УХЛ4), a multistage centrifugal compressor (K-250-61-2).

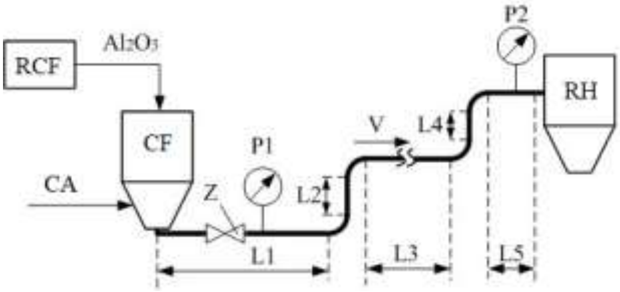


Fig. 1. Structural scheme of PTS experimental site

During the experiment, 42 measurements (n, pcs.) of pressure were made at the inlet and outlet of the pneumatic conveying system ($P \cdot 10^5$, Pa) near the chamber feeder with the P_1 gauge and at the pneumatic outlet near the receiving hopper with the P_2 gauge.

On Fig. 2 shows the results of measurements, according to which it was found that the difference in pressure loss reaches $2.45 \cdot 10^5$ Pa. The automatic control system must timely compensate for the loss of pressure in the pneumatic conveying lines, in order to avoid blockage, stopping the process of transporting bulk materials and clogging of pneumatic conveying systems [22]. According to the technological process, the pressure at the outlet of the system should be at least $2 \cdot 10^5$ Pa.

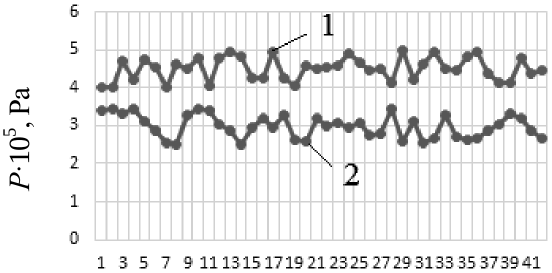


Fig. 2. Experimental data: pressure at the inlet (1) and outlet (2) of the PTS

To ensure this condition, the necessary speed of the mixture of air with alumina at the outlet of the pneumatic duct V, m/s was determined according to equation (1) [23]

$$V = \alpha \cdot \sqrt{\gamma} + \beta \cdot L_e^2, \tag{1}$$

where: α = 10 – coefficient taking into account the geometric dimensions of alumina particles; β = 0.00005 – coefficient taking into account changes in the specific gravity of air in the pneumatic transport line; γ = 3.5 ton/m^3, specific gravity of alumina particles; L_e – equivalent length of pneumatic conveyor.

$$L_e = L_g + L_v + L_p, \tag{2}$$

where: L_g – the total length of the horizontal sections of the pneumatic conveyor (3); L_v – the total length of the vertical sections of the pneumatic conveyor (4); L_p – total length of the rotations of the pneumatic conveyor (5).

$$L_g = L_1 + L_3 + L_5, \tag{3}$$

where: L_1 = 37 м; L_3 = 259 м; L_5 = 24 м

$$L_v = L_2 + L_4, \tag{4}$$

where: L_2 = 9,5 м; L_4 = 5,9 м

$$L_p = n_{90} \cdot k_{90}, \tag{5}$$

where: n_{90} = 4 – number of turns under the condition that the radius of turns is 5,1 m; k_{90} = 8 m – length of one turn. Then L_g = 320 m; L_v = 15.4 m; L_p = 32 m; L_e = 367.4 m

In the calculations, the equivalent length of the pneumatic race is taken L_e = 370 m.

As a result of the studies, the speed of the mixture of air with alumina was calculated V = 25,553 m/s, which is necessary to ensure the minimum allowable pressure at the outlet of the air duct.

It was found that reducing the pressure at the outlet of the PTS reduces the energy efficiency of the system as a whole, and can also lead to clogging of the conveying pipeline with bulk material. An unstable transportation process is characterized by a decrease in the distance between particles and an increase in the concentration of the solid phase [24-25]. To study the nature of blockage occurrence, the equation of transient gas filtration is used [26]. We select in the gas stream an elementary volume in the form of a parallelepiped with faces *dx*, *dy*, *dz* parallel to the corresponding coordinates and apply the law of conservation of mass to this expression (Fig. 3). If the velocity in the center of the parallelepiped at point A is equal to U and density ρ, we denote the projection of the velocity on the axis ox, oy, oz by

Ux, *Uy*, *Uz*. Then the mass flow rate (mass of gas flowing through the face *abcd* of the parallelepiped per unit time) [20; 27]:

$$dM_1 = \left[\rho U_x - \frac{1}{2}\frac{\partial(\rho U_x)}{\partial x}dx\right]dydz \quad (6)$$

The mass of gas flowing through the opposite side a_1, b_1, c_1, d_1:

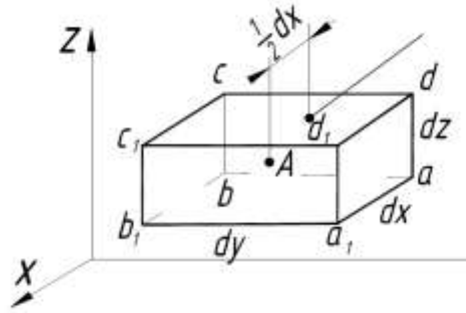


Fig. 3. The conditional elementary volume of the transported material in the gas stream

$$dM_{x1} = \left[\rho U_x + \frac{1}{2}\frac{\partial(\rho U_x)}{\partial x}dx\right]dydz. \quad (7)$$

In the direction of the axis *ox* per unit time, the inflow and outflow of the mass of gas in an elementary volume:

$$dM_x - dM_{x1} = -\frac{\partial(\rho U_x)}{\partial x}dxdydz. \quad (8)$$

At a constant temperature *T*, we obtain the equation for transient laminar gas filtration through a porous medium [24]:

$$\frac{c}{\varepsilon}\frac{\partial}{\partial x}\left(\rho\frac{\partial\rho}{\partial x}\right) = \frac{\partial\rho}{\partial t}, \quad (9)$$

where: *c* – is the filtration coefficient characterizing the filtration properties of the porous rock and the physical properties of the filtering fluid; ε – is the porosity coefficient of the medium.

With the formation of a block at the end of the cork, we select an element Δx. Pressure is applied to the cork:

$$P = \frac{\pi D^2}{4}\frac{\partial P}{\partial x}\Delta x, \quad (10)$$

where: *D* – is the diameter of the pipeline, m.

The force of friction that holds him in equilibrium:

$$F_{tr} = \tau\pi D\Delta x,$$

where: τ – is the allowable shear stress for clinker

$$\tau = \frac{D}{4}\left(\frac{\partial P}{\partial x}\right).$$

To satisfy the equilibrium condition in the piston, the tangential stress must not exceed the permissible τ at which the piston ruptures.

The condition of stability of the piston [26]:

$$\frac{\partial P}{\partial x} \le \frac{4\tau}{D}. \quad (11)$$

Based on the Darcy law and the continuity equation, an expression is obtained for finding the analytical dependence of the place of occurrence (L_1) of the possible blockage point on the pressure drop *(*ΔP*)* at the output of the pneumatic route:

$$L_1 = \frac{\Delta P(P_0 + P_1)D}{8P_0\tau}, \quad (12)$$

where: P_0, P_1 – pressure at the input and output of the PTS, respectively, Pa.

The section of the air duct with a low probability of occurrence of blockage L_2=*L*e-L_1; L_1 – site drain involved in the repair work in the event of a blockage; L_2 – a site located after the place of occurrence of the blockage and not requiring repair. The larger the L_1 section, the more reliable the TCP operation. To reduce the L_2 area, a large consumption of compressed air is required, which reduces the energy efficiency of the TCP.

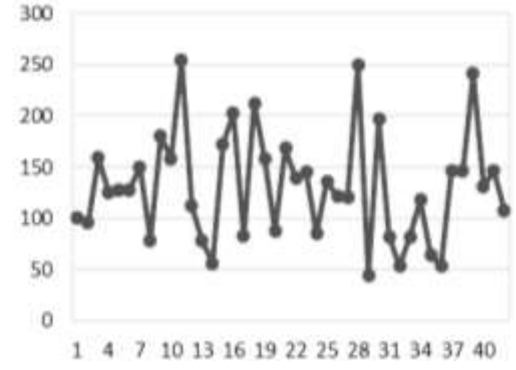


Fig. 4. Estimated cork lengths with a drop in pressure at the outlet of the PTS

Table 2 shows the results of a numerical calculation of the plug length for 42 measurements, with a section diameter *D* = 0.143 m; τ = 20.09 kg/m^2; the pressure values at the inlet and outlet of the TCP are shown in Table 2.

Table 2. Inlet and outlet pressure values routes and the corresponding ratios of the lengths of sections of

the pneumatic track with the place of the probable occurrence of block

No.	P_0, 10^5 Pa	P_1, 10^5, Pa	L_1, m	L_2, m
1	4.02	3.405	101.04	265.95
2	4.023	3.444	95.59	217.4
3	4.704	3.336	159.01	207.98
4	4.213	3.44	124.9	242.09
5	4.758	3.131	127.74	239.26
6	4.532	2.89	127.79	239.2
7	4.031	2.533	150.02	216.98
8	4.615	2.52	78.89	288.11
9	4.504	3.29	180.13	186.87
10	4.793	3.427	158.61	208.39
11	4.071	3.384	255.09	111.91
12	4.779	3.024	112.11	254.89
13	4.94	2.89	77.86	289.14
14	4.814	2.524	56.49	310.5
15	4.26	2.97	172.75	194.25
16	4.243	3.188	202.64	164.36
17	4.947	2.945	82.9	284.1
18	4.253	3.274	212.88	154.12
19	4.06	2.64	158.56	208.44
20	4.575	2.568	88.26	278.74
21	4.485	3.179	168.48	198.51
22	4.528	2.985	139.26	227.74
23	4.567	3.082	145.76	221.24
24	4.923	2.941	85.37	281.63
25	4.655	3.095	135.97	231.03
26	4.456	2.748	121.37	245.63
27	4.503	2.794	120.65	246.35
28	4.147	3.429	250.32	116.68
29	4.982	2.6	44.54	322.46
30	4.223	3.124	196.92	170.08
31	4.621	2.559	82.01	284.99
32	4.961	2.671	53.63	313.37
33	4.506	3.276	178.04	188.96
34	4.456	2.716	117.88	249.12
35	4.835	2.636	64.75	302.25
36	4.953	2.658	53.29	313.7
37	4.386	2.89	146.24	220.76
38	4.131	3.045	117.81	249.19
39	4.117	3.337	241.38	125.62
40	4.798	3.211	131.36	235.64
41	4.361	2.862	146.15	220.85
42	4.478	2.65	108.17	258.83

A variation in the calculated value of the tube length is shown in Fig. 4 the arithmetic average of the length of the block for 42 measurements of the pressure drop at the outlet of the PTS is 131.07 m.

Thus, the obtained value of L_1 is about a third of the entire length of the pipe wire and is the minimum step of influence on the transported two-phase flow in order to prevent the occurrence of bends.

In the course of the experiment (Table 2), it was determined that with the growth of the pressure difference, the probability of blockages is shifted towards the chamber feeder. The decrease in the pressure difference shifts the point of the probable occurrence of blockage towards the receiving hopper.

The values on the graph (Fig. 5), obtained in a practical way, reflect the linear nature of the dependence of the point of the probable occurrence of blockage (L_1) on the pressure difference at the inlet and outlet of the air duct (ΔP), which allows one to establish the place of the probable occurrence of the blockage and conduct its local elimination.

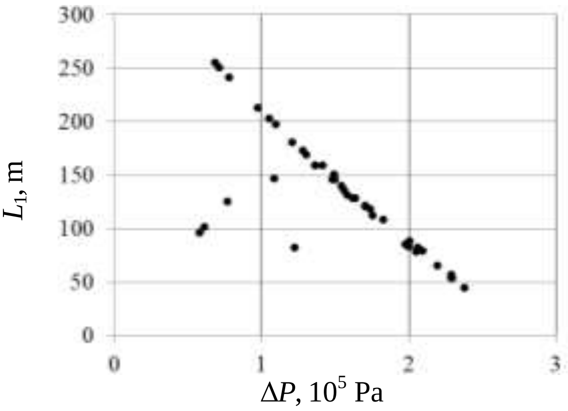


Fig. 5. The dependence of the points of probability of rebirth

It should be noted that in preparing air for pneumatic transportation of all materials, the air temperature and dew point temperature increase due to air compression. Subsequent cooling of the compressed air leads to its saturation, as well as to the formation of condensate. The condensate is partially trapped by special systems, but air with a humidity close to 100 % is supplied to the system for transportation. Thus, hygroscopic materials absorb moisture, stick together and begin to adhere to the internal surfaces of the PTS. Thus, there are problems with patency, as a result of which equipment stops. Air requirements in pneumatic transport systems depend on the characteristics of the transported material and are individual for each case under consideration [28]. The optimum relative humidity is in the range of 20-40 %.

One of the features to reduce the likelihood of blockages is the development of self-propelled guns taking into account the humidity control of compressed air supplied to the PTS and the humidity control of the alumina itself in order to reduce air humidity in pneumatic conveying systems.

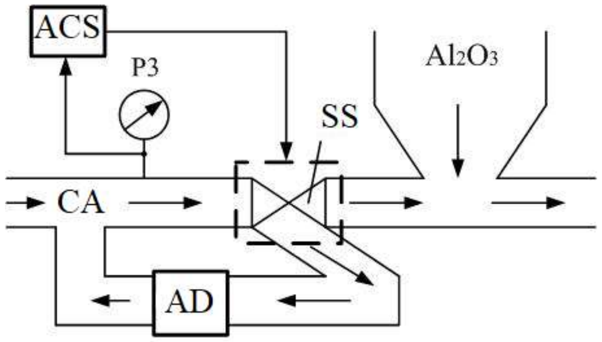


Fig. 6. The structural diagram of the drainage site

The structural diagram of the drainage area is shown on Fig. 6,
where: CA is the compressed air supplied for transportation; SS – stream splitter; AD – air dryer; P3 – moisture measure; ACS – automatic control system.

Compressed air is supplied by the compressor to the system; periodic instrumental measurement of the humidity of compressed air is carried out using the IVG-1 K-P moisture meter. The value of moisture measurements is supplied to the automatic control system, where they are compared with the permissible ones. If these values of compressed air humidity are exceeded, the ACS generates a control signal to switch the compressed air flow separator to the desiccant. When the parameters of compressed air are normalized, the SS switches to the pneumatic conveying system.

When developing new and modernizing existing self-propelled guns, it is advisable to use mathematical and computer models of these systems, which will save time and money on preliminary experiments [29-32]. A simplified functional diagram of the electric drive of the pneumatic-transport system is shown in Fig. 7,
where: ACS is an automatic control system; D – drive synchronous motor (SM) (СТД-1600-2УХЛ4); C – compressor (K-250-61-2 – multi-stage centrifugal compressor); Z – controlled valve; P1, P2 — pressure sensors at the input and output of the TCP, respectively; PTS – pneumatic conveying system, taking into account the trajectory and geometric dimensions; RH – receiving hopper.

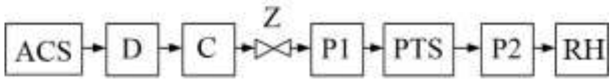


Fig. 7. Simplified functional diagram of the electric actuator of the pneumatic conveying system

To describe the dynamic modes of operation of a synchronous electric motor (SM) with any method of controlling its speed, it is convenient to refer to the model of a generalized two-phase AC machine [33]. This model allows you to go to the conditional vector description of electric machines of alternating current. The essence of the model of a generalized alternating current machine is that the action of the stator windings α and β, powered by the corresponding system of alternating voltage (current system I_α and I_β) and creating flux link vectors ψ_α and ψ_β at each specific instant of time, can be replaced by the action of a single winding powered by a direct current I_1 and rotating with a speed ω_0 of a magnetic field. The system of equations in operator form gives a description of the SD at a constant flow of the rotor in an orthogonal rotating coordinate system *(d, q)* [33]

$$\begin{cases} (T_{11}p+1)\psi_{1d} = T_{11}U_{1d} + \psi_B + \\ + T_{11}\omega Z_P \psi_{1q}, \\ (T_{11}p+1)\psi_{1q} = T_{11}U_{1q} - T_{11}\omega Z_P \psi_{1d}, \\ Jp\omega = \dfrac{m_1 Z_P \psi_B}{2L_1}\psi_{1q} - M_{C,} \end{cases} \tag{13}$$

where: *p* is the differentiation operator; $T_{11} = L_1 / R_1$ – electromagnetic time constant; U_{1d}, U_{1q} – components of the stator voltage; ψ_{1d}, ψ_{1q} – stator flux linkage vector; ψ_B – rotor flux linkage vector; Z_p – the number of pairs of poles; m_1 – the number of phases of the stator of the electric motor; *J* – is the moment of inertia reduced to the motor shaft.

For the input control actions, the rotation frequency of the magnetic field ω_0 and the voltage U_{1d} and U_{1q} are taken. The main disturbing effect is the moment *M*c of resistance forces, and the output coordinate ω is the angular speed of the electric motor rotor. The system of equations shows that the synchronous motor is a nonlinear control object [33]. The system of equations (13) was linearized by expanding the main nonlinear dependences into a Taylor power series in the vicinity of a certain working point with such parameters: $\psi_{1d0,}$ ψ_{1q0} [33]

$$\begin{cases} (T_{11}p+1)\psi_{1d0} = T_{11}U_{1d} + \psi_B + \\ + T_{11}\omega Z_P \psi_{1q0}, \\ (T_{11}p+1)\psi_{1q0} = T_{11}U_{1q} - T_{11}\omega Z_P \psi_{1d0}. \\ Jp\omega = \dfrac{m_1 Z_P \psi_B}{2L_1}\psi_{1q0} - M_{C.} \end{cases} \quad (14)$$

The system of equations (14) makes it possible to find the transfer functions of a synchronous electric motor from the control actions ω_0 and U_1.

$$W_D(p) = \frac{\omega(p)}{\omega_0(p)} = \frac{1}{T_{e1}T_{m1}p^2 + T_{m1}p + 1}. \quad (15)$$

$$T_{e1} = T_{11},\ \mathrm{T_{m1}} = \frac{2JR_1}{m_1 Z_P^2 \Psi_B \Psi_{1q0}}.$$

The speed of a synchronous motor in this mode is proportional to the voltage applied to the stator windings.

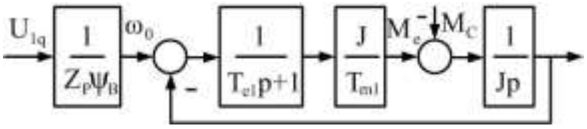


Fig. 8. Synchronous motor linearized description structure scheme

The compressor is characterized by gas-dynamic characteristics (pressure versus flow). If we take any point on the static characteristic of the supercharger, then we can trace its trajectory of motion when the compressor rotational speed changes [34].

Consider the mathematical model of the compressor installation along the second air flow circuit (Q). Therefore, we will stabilize the air flow at the given stage based on the set point. The model is presented without taking into account the gate valves and the secondary circuit by pressure, as well as the engine overheating, since this is implemented in hardware using a thermal relay, thus, the isothermal process [35]. The simplest theory of compressor machines, with acceptable accuracy, is based on the thermodynamics of an ideal gas. In this case, the Boyle-Marriotte law is used, i.e. the gas volume is proportional to the pressure at a constant temperature

$$PV = const,\ T = const.$$

To implement a centrifugal compressor in single pipelines, an aperiodic link of the second order is used; in this system, the delay is not taken into account. Thus, the transfer function of the compressor, in which the input signal is the angular speed of rotation of the drive motor shaft, and the output signal is the flow rate, is as follows

$$W_K(p) = \frac{\omega_0(p)}{Q(p)} = \frac{K}{(T_1p+1)(T_2p+1)}, \quad (16)$$

where: T_1, T_2 – compressor time constants, K – gain of the transfer function of the compressor.

The mathematical model of a pipeline with a liquid consists of equal costs at the inlet (node i) and output (node j) and the pressure loss equation along the length and has the form (17) [36]. When considering pneumatic transportation of a mixture of air with alumina, it is assumed that a mixture with a certain average density (pseudo-liquid) can be considered as a liquid.

$$\begin{cases} Q_i = Q_j, \\ P_j = P_i - \lambda \dfrac{8\rho L_{tr}}{\pi^2 D_{tr}^5} Q_i |Q_i|. \end{cases} \quad (17)$$

In system (17), L_{tr}, D_{tr} – the length and diameter of the pipeline; ρ is the density of the working fluid; λ is the coefficient of pressure loss along the length of the pipeline

$$\lambda = \begin{cases} 75/\mathrm{Re}\ \ npu\ \ \mathrm{Re} \le 2300, \\ 0{,}3164 \cdot \mathrm{Re}^{-0{,}25}\ npu\ \ \mathrm{Re} > 2300, \end{cases}$$

where: Re is the Reynolds number.

$$\mathrm{Re} = \frac{4|Q_i|}{\pi \cdot D_{tr} \cdot \nu},$$

where: ν is the kinematic viscosity $\nu = \eta/\rho$, η – is the dynamic viscosity of the liquid; η (air) = $1{,}8 \cdot 10^{-5}$ Pa·c; ρ (alumina) – 3.5-3.9 g/sm^3; $L_{tr} = L_e = 370$ м; $D_{tr} = D = 0{,}143$ м.

Based on the mathematical description (2)-(5), (12), (15)-(17), a computer model of the electric drive of the pneumatic conveying system was compiled (Fig. 9) and the electro-mechanical processes of this system were obtained (Fig. 10) by means of Matlab-Simulink.

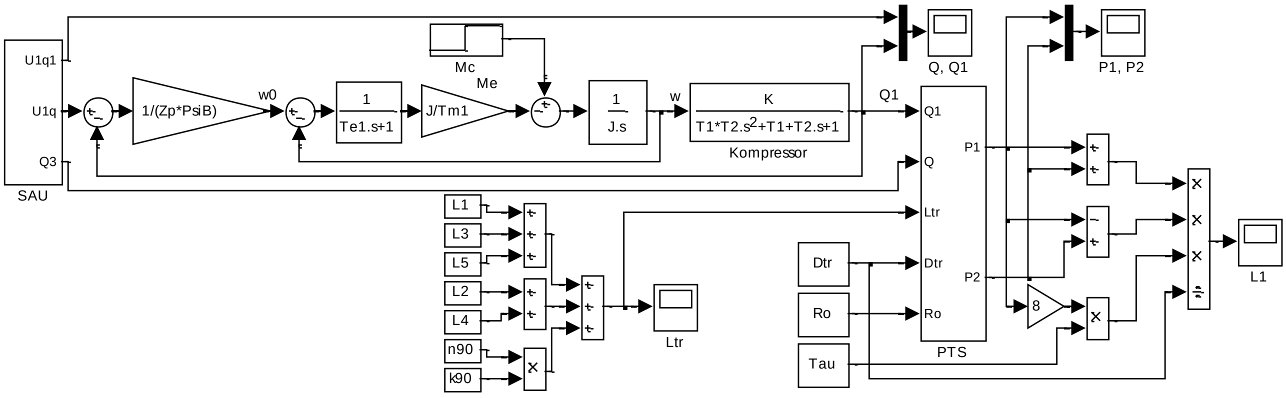
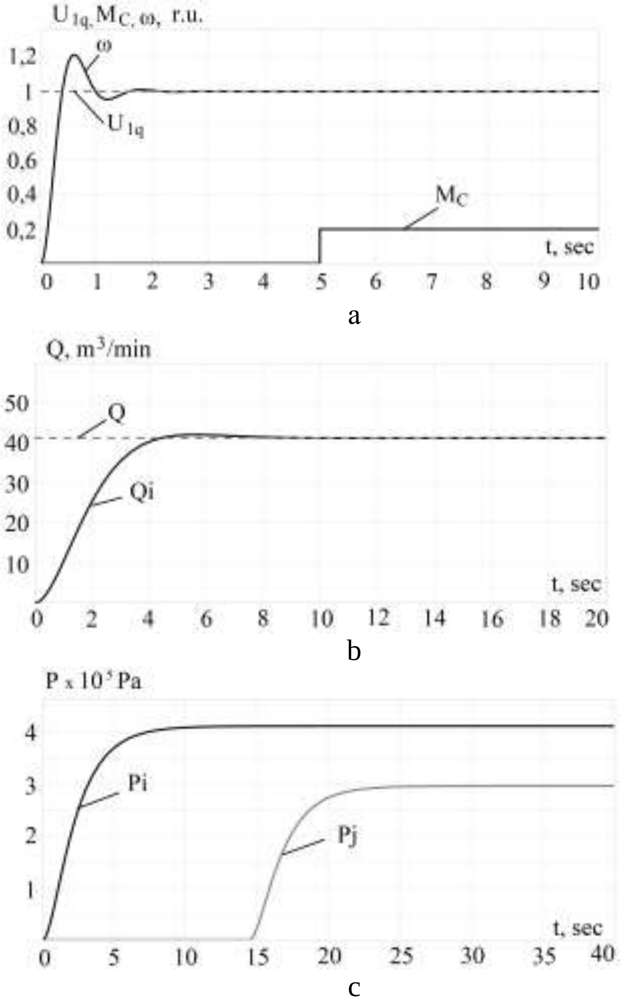


Fig. 9. Computer model of an electric drive pneumatic conveying system



a

b

c

Fig. 10. Electromechanical processes pneumatic transport system: SM transient processes, taking into account the attached rated load Mc (a), compressor electric drive transient processes (b), simulation results of pressure at the inlet P_i and at the output P_j of the air duct (c)

Fig. 10a shows the start of the compressor drive motor, since the synchronous motor model is simplified linearized, the features of its start are not reflected in the graphs. Upon reaching a steady-state value of air flow (Fig. 10b), Al_2O_3 is supplied from the chamber feeder, which is modeled as an application of the resistance moment at $t = 5$ sec. With a PTS length of about 370 m and a linear velocity of the mixture V = 25.553 m/sec, the pressure at the PTS outlet will appear in 14.48 sec, which is shown in Fig. 10c.

The obtained graphs of the electromechanical processes of the PTS electric drive confirm the adequacy of the developed mathematical and computer models with an error of 10-12 % for steady regime.

Conclusions. Because of experimental studies, it was found that reducing the pressure at the outlet of the PTS, exceeding the permissible humidity of compressed air supplied to the PTS, reduces the energy efficiency of the system as a whole, and can also lead to blockages.

With aim of reducing the consumption of electric energy by a pneumatic transport system, it is proposed to transport raw materials at a speed that ensures the minimum pressure that is permissible by the technological process.

The average pressure at the inlet of the PTS was $4.5 \cdot 10^5$ Pa, at the outlet of the PTS – $2{,}98 \cdot 10^5$ Pa, thus, the pressure drop at the outlet was about 30 %. The calculations showed that, on average, the place of probable blockage with these data will be removed from the prefabricated bunker by L_1 = 131.07 m with a total length of the experimental section of about 370 m. The obtained value of L_1 is about a third of the entire length of the pipeline and It is the minimum step of impact on the transported two-phase flow in order to prevent the occurrence of blockages. It has been established that with an increase in the pressure difference at the inlet and outlet of the PTS, the place of the probable occurrence of blockage shifts to the chamber feeder.

An analytical dependence of the place of occurrence of a possible clogging point on the pressure drop at the outlet of the pneumatic flow was obtained, which allows us to determine the minimum step of the impact on the transported two-phase flow in order to prevent the occurrence of blockages and, if necessary, to determine the place of its occurrence.

Mathematical and computer models of the electric drive of the pneumatic transport system have been developed; graphs of electromechanical processes have been obtained, confirming its adequacy with an error of 10-12 % for steady regime. The use of these models will save time and money on conducting preliminary experiments when developing new and modernizing existing PTS.

For a more rational use of energy resources by stabilizing the pressure during the development of the automatic control system of the PTS, it is recommended to predict a change in its electromechanical parameters taking into account the location of a possible blockage of the PTS and introduce an additional pressure control signal, thereby reducing energy consumption and material costs associated with the elimination of blockages.

References

1. Harald Wilms. (2019). “Pneumatic conveying: optimal system design, operation and control pneumatic conveying”. – Available at: https://www.chemengonline.com/pneumatic-conveying-optimal-system-design-operation-and-control/ – Access date: 14.03.2019.

2. D. Mills. (2004). “Pneumatic Conveying Design Guide”. Elsevier Butterworth-Heinemann, 637 p.

3. Gomes, L. M. & Mesquita, Andre. (2013). “Effect of particle size and sphericity on the pickup velocity in horizontal pneumatic conveying”. *Chemical Engineering Science*, No. 104, pp. 780-789.

4. Marcus, R. D., Leung, L. S, Klinzing, G. & Rizk, Fadi. (1993). “Pneumatic Conveying of Solids: A Theoretical and Practical Approach”. *Drying Technology*, No. 11, pp. 859-860.

5. Gomes, M. L. & Mesquita, Andre (2014). “On the prediction of pickup and saltation velocities in pneumatic conveying”, *Brazilian Journal of Chemical Engineering*, No. 31, pp. 35-46.

6. Anantharaman, Aditya, Cahyadi, Andy, Hadinoto, Kunn & Chew, Jia Wei. (2016). “Impact of particle diameter, density and sphericity on minimum pickup velocity of binary mixtures in gas-solid pneumatic conveying”, *Powder Technology*, No. 297, pp. 311-319.

7. Mehdizad, M. & Kouhikamali, Ramin (2018). “Numerical investigation of the minimum fluidization velocity in a gas–solid fluidized bed using discrete phase model”. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, No. 40, pp. 272-282, doi: 10.1007/s40430-018-1176-7.

8. Liang, Cai, Grace, John, Shen, Liu, Yuan, Gaoyang, Chen, Xiaoping & Zhao, Changsui (2015). “Experimental Investigation of Pressure Letdown Flow Characteristics in Dense-phase Pneumatic Conveying at High Pressure”. *Powder Technology.* Vol. 277, pp. 171-180, doi: 10.1016/j.powtec.2015.03.002.

9. Klinzing, G., Rizk, Fadi, D. Marcus, R & S. Leung, L. (2010). “An Overview of High-Pressure Systems Including Long-Distance and Dense Phase Pneumatic Conveying Systems”. *Pneumatic Conveying of Solids. Particle Technology Series*, Vol. 8, pp. 331-355, doi: 10.1007/978-90-481-3609-4_9.

10. Marcus, R. D. (1984). “Minimum energy pneumatic conveying”. I: Dilute phase. *Journal of Environmental Quality*, No. 13, pp.113-121.

11. Lohrmann, P. C. & Marcus, R. D. (1984). “Minimum energy pneumatic conveying, II – dense phase”. *Journal of pipelines*, No. 4, pp.123-129.

12. Anantharaman, Aditya, Cahyadi, Andy, Hadinoto, Kunn & Chew, Jia Wei. (2016). “Impact of particle diameter, density and sphericity on minimum pickup velocity of binary mixtures in gas-solid pneumatic conveying”. *Powder Technology*, No. 297, pp. 311-319.

13. Mehdizad, M. & Kouhikamali, Ramin (2018). “Numerical investigation of the minimum fluidization velocity in a gas–solid fluidized bed using discrete phase model”. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, No. 40, pp. 272-280, doi: 10.1007/s40430-018-1176-7.

14. Xiang, Junting & New, T. H. (2019). “Numerical investigations on a small-scale air-slide conveyor”. *Journal of Applied Fluid Mechanics*, No. 1, pp. 1-9, doi: 10.18869/acadpub.jafm 75.253.29219.

15. Jens, Garbe, Arne, Hilck & Andreas, Wolf. “Pneumatic conveying of alumina – comparison of technologies”. – Available at: https://icsoba.org-/sites/default/files/2015paper/aluminiumpapers/AL08%20-%20Pneumatic%20conveying%20of%-20alumina%20-%20comparison%20of%-20technologies.pdf – Access date: 30.03.2019.

16. Bhatia, A. (2019). “Pneumatic Conveying Systems”. – Available at: https://www.cedengineering.com /courses/pneumatic-conveying-systems – Access date: 14.03.2019.

17. Kraus, N. Milton (1968). “Pneumatic conveying of bulk materials”. New York, USA, 338 p.

18. Hu, Shengyong, Zhou, Fubao, Geng, Fan, Liu, Yingke, Zhang, Yifan & Wang, Qingxiang (2014). “Investigation on blockage boundary condition of dense-phase pneumatic conveying in bending slits”. *Powder Technology*, No. 266, pp. 96-105.

19. Zhang, Yifan, Zhou, Fubao, Xia, Tongqiang, Liu, Chun, Wang, Xinxin, Liu, Jun & Chen, Yazeng. (2015). “Experimental Investigation on Blockage Boundary for Pneumatic Conveying of Powders in Narrow Bifurcation Slits”. *Drying Technology*, Vol. 34, pp. 1052-1062, doi: 10.1080/07373937.2015.1092157.

20. Zenz, F. A. & Othmer, D. F. (1960). “F1uidization and Fluid-Particle Systems, Reinhold”. New York, USA, 513 p.

21. Rogovoj, A. S. (2016). “Energeticheskaia effektivnost pnevmotransportnykh ustanovok”. [Energy efficiency of pneumatic conveying systems]. *Visnik Skhidno-ukrainskogo natsionalnogo universitetu imeni Volodimira Dalia,* No. 1 (225), pp. 189-196 (in Russian).

22. Fabio, Novelli & Mike, Weyandt. (2019). “A quick look at pneumatic conveying system basics”. – Available at: https://www.powderbulk.com/wp-content/ uploads/2014/05/pbe_20100301_0030.pdf – Access date: 14.03.2019.

23. Nazarova, E. S., Bondarenko, V. I. & Meleshko, I. A. (2018). “Issledovanie yavleniya transportnogo zapazdyvaniya v pnevmotransportnoy sisteme sypuchikh materialov”. [The research of transport delay occurrence in pneumatic transport system of the bulk materials]. *Problems of energy saving in electrical systems. Science, formation and practice*. Kremenchug, Ukraine, No. 5, pp. 27-29 (in Ukrainian).

24. Ostrovskiy, G. M. (1984). “Pnevmaticheskii transport sypuchikh materialov v khimicheskoi promyshlennosti”. [Pneumatic trans-port of loose materials in the chemical industry]. Leningrad, Russian Federation, 104 p. (in Russian).

25. Timoshenko, V. I. & Knyshenko, Ju. V. (2013). “Pnevmotransport sypuchikh materialov s povy-shennym davleniem nesushchego gaza”. [Pneumo-transport of bulk materials with increased pressure of the bearing gas]. *Nauka ta innovatsii*, Vol. 9, No. 1, pp. 5-17 (in Russian).

26. Malykhina, N. A. & Pogonin, A. P. (2001). “Yavlenie zavala i matematicheskaya mo-del' opisaniya zavala v pnevmotransportnykh sistemakh”. [The phenomenon of obstruction and a mathematical model for describing obstruction in pneumatic conveying systems]. *Miner's Week*, pp. 216-217 (in Russian).

27. Razumov, I. M. (1972). “Psevdozhizhenie i pnevmotransport sypuchikh materialov”. [Fluidization and pneumatic conveying of loose materials]. Moscow, Russian Federation, 240 p. (in Russian).

28. Tarasov, V. P., Glebov, A. A. & Gejneman A. E. (1999). “Raschet pnevmotransportnykh ustanovok”. [Calculation of pneumatic conveying systems]. *Izvestija vuzov. Pischevaja tehnologija*, No. 2-3, pp. 77-81 (in Russian).

29. Sadovoi, O. V., Nazarova, O. S., Bondarenko, V. I. & Pirozhok, A. V. (2014). “Novoe v modelirovsnii I issledovsnii elektromekhanicheskih system stanov kholodnoi prokatki”. [New in modeling and research of electromechanical systems of cold rolling mills]: monographia Zaporizhzhia, Ukraine, *“Prosvita”*, 144 p. (in Russian).

30. Nazarova, O. S. (2015). “Matematicheskoe modelirovanie elektromekhanicheskih system stanov kholodnoi prokatki”. [Mathematical modeling of electromechanical systems of cold rolling mills]. Kiev, Ukraine, *Tehnichna elektrodinamika*, No. 5, pp. 82-89 (in Russian).

31. Nazarova, O. S. (2019). “Modelirovanie elektromehanicheskih protsesov vzaimosviazannih mnogomassovih system”. [Modeling of electromechanical processes of interconnected multi-mass systems]. Tbilisi, Georgia, *Energia*, pp. 60-64 (in Russian).

32. Nazarova, O. S., Osadchyy, V. V., Meleshko, I. A. & Oleinikov, M. O. (2019). “Identifikaciia kutovoi shvidkosti pri zavadah v optichnii sistemi enkodera”. [Identification of angular velocity during interference in the optical encoder system]. Kharkiv, Ukraine, *Visnik NTU “KhPI”,* pp. 65-69 (in Ukrainian).

33. Rudnev, E. S. & Morozov, D. I. (2016). “Linearizovanaia matematicheskaia model sinhronnogo dvigatelia s postoiannimi magnitami kak obiekta upravleniia”. [Linearized mathematical model of synchronous engine with permanent magnets as a control object]. Donetsk, Ukraine, *Zbirnik naukovih prats DonDTU,* No. 1(45), pp. 88-93 (in Russian).

34. Lupinos, O. N., Pylypenko, D. V. & Fedun, R. V. (2009). “Avtomaticheskoe upravlenie

kompressornoi stanstiei ochistnih sooruzhenii”. [Automatic control the compressor cleansing buildings]. Donetsk, Ukraine, *Naukovi pratsi DonNTU*, No. 148, pp. 30-36 (in Russian).

35. Shamina, V. A. (2012). “Avtomatizaysiia tehnologichnih obiektiv ta protsesiv. Poshuk molodih”. *Zbirnik naukovih prats XII naukovo-tehnichnoi konferentsii aspirantiv ta dtudentiv*. Donetsk, Ukraine, DonNTU, pp. 269-299 (in Ukrainian).

36. (2019). “Truboprovod” [Pipeline]. – Available at: http://www.simumath.net/library/book.html?codeHYSTR_library. – Access date: 06.06.2019.

Received 03.01.2020
Received after revision 28.01.2020
Accepted 14.02.2020

УДК 004.9:681.51:51-74

[1]**Назарова, Олена Сергіївна**, кандидат техніч. наук, доцент кафедри електропривода і автоматизації промислових установок, E-mail: nazarova16@gmail.com,
Scopus ID: 56826084800, ORCID: http://orcid.org/ 0000-0002-0784-7621
[1]**Мелешко, Ірина Анатоліївна**, аспірант кафедри електропривода і автоматизації промислових установок, E-mail:iameleshko@gmail.com, ORCID: http://orcid.org/ 0000-0003-2473-5434
[1]Національний університет «Запорізька політехніка», вул. Жуковського, 64, Запоріжжя, Україна, 69063

ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ І КОМП’ЮТЕРНЕ МОДЕЛЮВАННЯ ОСОБЛИВОСТЕЙ ВИНИКНЕННЯ ЗАВАЛІВ ПНЕВМОТРАНСПОРТНИХ СИСТЕМ

Анотація. *При проектуванні нових і модернізації існуючих пневмотранспортних систем необхідно враховувати зміни електромеханічних параметрів роботи обладнання при пуску або інших перехідних режимах, найбільш небезпечних з точки зору виникнення завалу пневмотраси. З огляду на високу вартість електроенергії і великі обсяги виробництва при транспортуванні сипких матеріалів, актуальним завданням є зниження питомої витрати стисненого повітря при транспортуванні, врахування при розробці систем автоматичного керування основних факторів, а саме, втрату тиску на виході пневмотраси, що впливають на виникнення завалів пневмотранспортних систем. Метою роботи є проведення експериментальних досліджень і комп'ютерного моделювання особливостей виникнення завалу пневмотранспортних систем при транспортуванні сипучих матеріалів, пов'язаних з втратою тиску на виході пневмотранспортних систем. Поставлена мета досягається за рахунок проведення експериментів, на підставі яких отримано аналітичний вираз для визначення швидкості руху суміші, що забезпечує мінімально допустимий за технологічним процесом тиск на виході пневмотраси. Встановлено аналітичну залежність виникнення можливої точки закупорки від падіння тиску на виході пневмотраси, що визначає мінімальний крок впливу на транспортований двофазний потік з метою перешкоджання виникненню завалів, а також при необхідності вказує на місце виникнення завалу. Встановлено, що при збільшенні різниці тиску на вході і виході трубопроводу точка можливої закупорки зміщується в бік камерного живильника. Стабілізація вологості стисненого повітря, що подається в пневмомагістраль, за рахунок використання більш чутливого і швидкодіючого вимірювального обладнання та засобів автоматизованого керування знизить можливість виникнення завалу, забезпечить економію електроенергії, а отже, підвищить ефективність пневмотранспортной системи. Розроблено математичну і комп'ютерну моделі електроприводу пневмотранспортной системи, отримано графіки електромеханічних процесів, що підтверджують її адекватність з точністю десять-дванадцять відсотків. Використання названих моделей дозволить заощадити час і кошти на проведення попередніх експериментів при розробці нових і модернізації існуючих пневмотранспортних систем.*

Ключові слова: *комп’ютерне моделювання; пневмотранспортна система; сипкі матеріали; стиснене повітря; енергоефективність.*

УДК 004.9:681.51:51-74

[1]**Назарова, Елена Сергеевна**, кандидат технических наук, доцент кафедры электропривода и автоматизации промышленных установок, E-mail: nazarova16@gmail.com,
Scopus ID: 56826084800, ORCID: http://orcid.org/ 0000-0002-0784-7621
[1]**Мелешко, Ирина Анатольевна**, аспирант кафедры электропривода и автоматизации

промышленных установок, E-mail:iameleshko@gmail.com,
ORCID: http://orcid.org/ 0000-0003-2473-5434
[1]Национальный университет «Запорожская политехника», ул. Жуковского, 64, Запорожье, Украина, 69063

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ И КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ ОСОБЕННОСТЕЙ ВОЗНИКНОВЕНИЯ ЗАВАЛОВ ПНЕВМОТРАНСПОРТНЫХ СИСТЕМ

Аннотация. *При проектировании новых и модернизации существующих пневмотранспортных систем необходимо учитывать изменения электромеханических параметров работы оборудования при пуске или других переходных режимах, наиболее опасных с точки зрения возникновения завала пневмотрассы. Учитывая высокую стоимость электроэнергии и большие объемы производства при транспортировке сыпучих материалов, актуальной задачей является снижение удельного расхода сжатого воздуха при транспортировке, учет при разработке систем автоматического управления основных факторов, а именно, потерю давления на выходе пневмотрассы, влияющих на возникновения завалов пневмотранспортных систем. Целью работы является проведение экспериментальных исследований и компьютерного моделирования особенностей возникновения завала в пневмотранспортных системах при транспортировке сыпучих материалов, связанных с потерей давления на выходе пневмотранспортной системы. Поставленная цель достигается за счет проведения экспериментов, на основании которых получено аналитическое выражение для определения скорости движения смеси, обеспечивающей минимально допустимое по технологическому процессу давление на выходе пневмотрассы. Получена аналитическая зависимость возникновения возможной точки закупорки от падения давления на выходе пневмотрассы, определяющая минимальный шаг воздействия на транспортируемый двухфазный поток с целью препятствия возникновению завалов, а также при необходимости указывающая на место возникновения завала. Установлено, что при увеличении разности давления на входе и выходе трубопровода точка возможной закупорки смещается в сторону камерного питателя. Стабилизация влажности сжатого воздуха, подаваемого в пневмомагистраль, за счет использования более чувствительного и быстродействующего измерительного оборудования, и средств автоматизированного управления снизит возможность возникновения завала, обеспечит экономию электроэнергии, а следовательно, повысит эффективность пневмотранспортной системы. Разработаны математическая и компьютерная модели электропривода пневмотранспортной системы, получены графики электромеханических процессов, подтверждающие её адекватность с точностью десять-двенадцать процентов. Использование названых моделей позволит сэкономить время и средства на проведение предварительных экспериментов при разработке новых и модернизации существующих пневмотранспортных систем.*

Ключевые слова*: компьютерное моделирование; пневмотранспортная система; сыпучие материалы; сжатый воздух; энергоэффективность*

Olena Sergiivna Nazarova, Candidate of Technical Sciences, Associate Professor
Research field: modeling of electromechanical systems; development and research of automation means of technological complexes and mechatronic systems; electromechanical systems with microprocessor control; methods and means of measuring, controlling, monitoring, and diagnosing of industrial equipment

Irina Anatoliivna Meleshko, PhD Student
Research field: research and computer modeling of pneumatic conveying system; development and research of automatic control system, electromechanical systems and electric drives