

CONSIDERATION OF PIPELINE ASCENDING SECTIONS DURING THE ROCK MOVEMENT IN PNEUMATIC TRANSPORT SYSTEMS

Ponomarenko S., Riabtsev O., Kabakova L.

M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine

Abstract. Keeping mining waste in the mine and using it to backfill the mined-out space can solve environmental problems and mining engineering tasks, primarily rock pressure control. One way to solve these problems is to use a pneumatic backfilling method, which makes it possible to achieve a high density of the filling massif. The subject of the research is the physical processes in pipeline pneumatic transport systems with ascending sections. The topic of the work is to evaluate the resistance of transport pipeline elements with ascending sections to the movement of air mixture and the influence of the angle of inclination on the characteristics of the air mixture flow at the outlet of the pneumatic transport system. The purpose of the work is to obtain a determining equation that describes the movement of the air mixture through a pipeline of constant diameter, taking into account the local hydraulic resistances in certain sections of the pipeline that change the direction of the air mixture. The determining equation contains the angle of inclination of the transport pipeline axis to the horizon $\omega > 0^\circ$, so this equation can be adapted to the conditions of transportation in a horizontal ($\omega = 0^\circ$) or vertical ($\omega = 90^\circ$) direction. The methodology of the work consists in applying a phenomenological approach to determining the resistance forces of the two-phase flow of “gas – solid particles” in a cylindrical pipeline. The influence of the resistance characteristics of straight and curved pipeline elements on the technological and design parameters of the pneumatic transport system is taken into account by the additivity of these parameters for each individual element. The scope of application of the results is the development of the scientific foundations of the theory of two-phase “gas – solid particles” flow in pipeline systems for pneumatic transport of dispersed materials in a dense phase. The implementation of the research results in engineering methods for calculating existing and new pneumatic transport systems will increase their efficiency in technological processes for moving dispersed materials at mining and metallurgical enterprises and in other industries.

Keywords. Pneumatic transport system, resistance coefficient, transport pipeline, ascending section, air mixture.

1. Introduction

In mining operations, waste from the extraction of minerals is in most cases deposited on the surface. The volume of this waste increases as thick coal seams are depleted and the number of shallow coal and thin ore seams increases. As thick coal seams are depleted and the number of shallow coal and low-power ore deposits increases, the volume of the waste is growing. The waste from mineral processing also causes significant damage to the environment. The existence of huge accumulations of man-made residues from the extraction and processing of minerals makes the problem of their disposal extremely acute [1–3].

One of the ways to solve the problem of environmental protection during underground mining of minerals in both the mining and coal industries is the pneumatic backfilling of the mined-out space in mines. This technology for the disposal of mining waste can be used when extracting deposits using various mining systems, regardless of the thickness and dip angles of the seams. The main element of this mining technology is pneumatic pipeline transport, which is widely used in many technological processes for moving various types of dispersed materials [4–6].

Today, there are several technologies for extracting minerals with complete backfilling of the mined-out space. All these technologies have one significant drawback—they do not allow filling more than 70–80% of the volume of the mined rock mass. To increase the efficiency of the technology for backfilling the mined-out space of mines, the IGTM of the National Academy of Sciences of Ukraine has developed a

standard range of vibration-pneumatic machines (VPM) with an annular ejector. This equipment belongs to the class of sectional pneumatic transport and allows, when performing backfilling works, to increase the percentage of filling of the mined-out space to 90% and even more. The use of a complex effect of vibration and aerodynamics on dispersed material in the VPM makes it possible to transport various types of bulk materials (including sticky and wet rocks). The VPM can be used both independently and as part of backfilling complexes in various technological processes of mining, primarily in technologies for the disposal of mining waste and the processing of minerals in the mined-out space [7, 8].

There are numerous studies that examine one of the most important parameters of pneumatic transport of bulk materials, which directly affects the energy efficiency of pneumatic transport systems (PTS). This parameter is the drop in compressed air pressure, which depends primarily on:

- the flow rate of the air and dispersed phases of the air mixture;
- the geometric and design characteristics of the transport pipeline;
- the physical and mechanical properties of the dispersed phase of the air mixture.

Research on pneumatic transportation of bulk food products with pulsed compressed air supply in a vertical pipeline was conducted in [5], where, as a result of analyzing a mathematical model based on differential equations of movement of individual particles in an air flow, the components of total air pressure losses in the pipeline were established. In addition, the work notes that the direct solution of the differential equations is quite problematic, and the use of empirical methods does not provide a complete calculation of the parameters of a two-phase flow.

Another area of research into the pneumatic transport of bulk materials, which has a long history, is the determination of energy costs to overcome the resistance forces of the air mixture. For example, the results of experimental studies on the influence of the structure of the solid phase resistance components of an air mixture, in which sawdust was used, on its mass flow rate and air pressure in the PTS are presented in [9].

In most pneumatic transport processes for bulk materials, a common problem is determining the effect of the total resistance of the pipe network, which may include horizontal pipes, vertical pipes, and elbows or other sections connecting network elements. The theoretical equations of movement in the pneumatic transport system of a mixture of air and fibrous waste in the ascending section of the pipeline and the relationship between the angle of expansion of the pipe and local resistances are given in [10]. The results of experimental studies of the effect of the orientation of the elbow (horizontal and vertical) of the transport pipeline on the total pressure drop at the elbow are given in [11].

The results of experimental studies of the friction coefficient of a fully suspended dilute flow of granular solid particles (granulated semolina, fly ash, and alumina) during their transportation through a pipeline with angles of inclination to the horizontal plane in the range from 0° to 30° are presented in [12].

Based on the concentration of the air mixture flow and its transport speed, the flow modes during transport are divided into zones:

- dilute phase (granulated particles or finely fractionated bulk material and powders);
- dense phase (coarse-grained bulk material with a fraction size greater than 5 mm) of the air mixture.

An analysis of recent PTS studies shows that pneumatic transport of diluted phase air mixtures is most widely used in all industries, despite the different transport pipeline network configurations. The disposal of waste from the extraction and processing of minerals in the mined-out space of mines using the PTS involves the pneumatic transport of dense phase air mixtures. Given the technological schemes of mining operations with pneumatic backfilling of the mined-out space, the PTS transport pipeline has to have a complex configuration with one or more ascending sections. At the same time, mine air supply networks have limited capabilities to increase the air pressure required for backfilling operations. One option for solving this problem is, for example, the use of mobile mine air blowers in combination with VPM, where air flow is more important than air pressure [7]. However, the issue of the transport distance of the backfill material, which, along with the density of the backfill mass, is one of the main technological characteristics, requires a more detailed study of the losses of pneumatic energy to overcome the resistance forces of the air mixture.

In backfilling operations, the process of pneumatic transportation through a pipeline of an air mixture consisting of rock particles and air is characterized by the fact that mechanical work is expended to overcome the resistance force of the air and dispersed phases of the air mixture. The magnitude of this integral force is estimated through the integral (generalized) coefficient of resistance to the movement of the air mixture in the transport pipeline, which in general is determined as a combination of the following factors:

- friction resistance of the air and dispersed phases of the air mixture against the walls of the pipeline;
- aerodynamic drag of the air environment;
- friction between particles of the dispersed phase of the air mixture.

When considering this complex interaction mechanism, a combination of various analytical and experimental research methods is used. As a result of such research by various authors, as mentioned above, dependencies have been obtained for the transport of the diluted phase of the air mixture, which are empirical due to the complexity of the interaction of the mixture components with each other and with the walls of the transport pipeline. Along with studying the friction mechanism, friction resistance is also evaluated based on the main parameters of the air mixture flow:

- volume or mass concentration;
- velocity;
- pipeline diameter;
- physical and mechanical properties of the transported material.

As a results of experimental studies of pneumatic transport of dense phase air mixtures, conducted by many foreign and domestic scientists (in particular, A.E. Smoldyriev, I.M. Razumov, and L.S. Kliachko), the dependence of the friction coefficient on the Reynolds number for different conditions and modes of transporta-

tion was obtained. According to the results of research by A.E. Smoldyriev, who is one of the pioneers in the development of pneumatic transportation systems for enterprises in the mining and metallurgical industry, the possibility of additional losses of pneumatic energy has been established, caused by the following:

- an increase in the concentration of the solid phase of the air mixture in the bottom part of the pipeline with a decrease in the speed of pneumatic transportation, which is especially characteristic of a change in the direction of movement of the air mixture;
- an increase in the possibility of collision between particles of the dispersed phase of the air mixture due to an increase in their concentration.

The purpose of this work is to obtain a defining equation for the patterns of air mixture movement through a pipeline of constant diameter in order to determine the main technological parameters of pneumatic transportation of rock. In accordance with the purpose, the research task is to take into account local hydraulic resistances that are present in certain sections of the pipeline and change the direction of air mixture movement. In addition, the work considers the influence of the angles of connecting elements of straight sections of the pipeline on the distance of rock transportation, which requires additional losses of compressed air pressure.

2. Methods

The research methods are: generalization of the results of theoretical and experimental studies of the movement of air mixture through the PTS pipeline with resistance of the individual sections; fundamental principles of two-phase flow mechanics “gas – solid particles”; modeling the movement of air mixture through a pipeline of constant diameter, taking into account its resistance, as well as obtaining approximate functions for determining the equivalent length of the PTS pipeline and the coefficient of local hydraulic resistance to the movement of air mixture depending on the angle of inclination of the pipeline section.

3. Theoretical part

The kinematics of transporting dispersed material through the PTS pipeline [13] is much more complex than the movement of an air mixture in space between two parallel walls. However, the basic nature of the movement of two-phase “gas – solid particles” flow along and across the pipeline axis is well described within the framework of a plane problem [4, 14, 15]. Regardless of the solved tasks, in the PTS transport pipeline, the energy of the air flow (pressure) is spent on moving the dispersed phase of the air mixture and overcoming various types of resistance. In general, the movement of bulk material particles in these systems occurs under the action of forces: aerodynamic (head) drag, gravity, Magnus-Zhukovskiy, interphase viscous friction in the air mixture (determined by Stokes' law), Saffman, and Archimedes.

For the movement of dispersed phase particles in an air mixture in air flow, the following forces can be disregarded [7, 15, 16]:

- Magnus-Zhukovskiy force, which depends on the angular velocity of rotation of the solid phase particles in the air mixture;

- Saffman, which manifests itself only for very fine particles (neglecting the force of interphase friction);
- Archimedes, the magnitude of which depends on the difference in density between the solid and air phases of the air mixture.

The following assumptions are made:

- the dispersed phase of the air mixture is a lumpy medium consisting of homogeneous solid particles with a density of ρ_s ;
- a pipeline with a length L_{pip} has a constant diameter D_{pip} and an angle of inclination of its axis to the horizon ω ;
- the air mixture moves in accordance with the isothermal law with a constant temperature T .

Taking into account the above, let us consider for a flat problem the movement of an air mixture through the PTS pipeline in accordance with the calculation scheme, a general view of which is shown in Fig. 1, where:

- P_1 and P_2 are the static air pressure at the beginning and end of the pipeline, Pa;
- $\rho_{a,1}$ and $\rho_{a,2}$ – air density at the beginning and end of the pipeline, kg/m³;
- u_1 and u_2 – air velocity at the beginning and end of the pipeline, m/s;
- v_1 and v_2 are the velocity of the dispersed phase particles of the air mixture at the beginning and end of the pipeline, m/s.

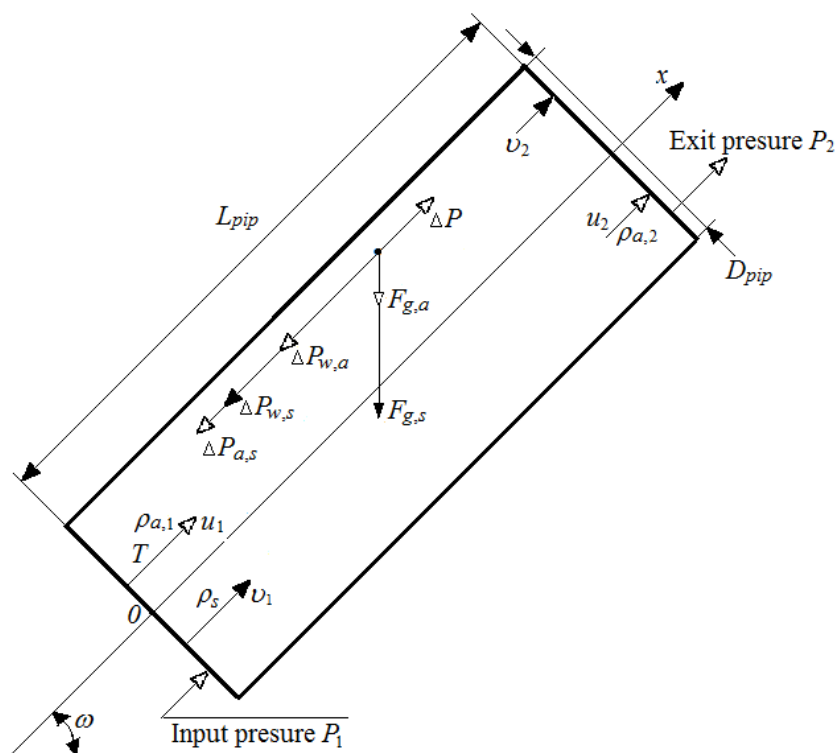


Figure 1 – Calculation diagram of air mixture movement in the ascending section of the pipeline

Ignoring the force of interphase viscous friction and taking into account the accepted assumptions, according to the calculation scheme (Fig. 1), the distribution of pressure losses ΔP in the ascending section of the PTS pipeline is as follows:

$$\Delta P = \Delta P_{a,s} + \Delta P_{w,s} + \Delta P_{w,a} + \Delta P_{g,s} + \Delta P_{g,a}, \quad (1)$$

where $\Delta P_{a,s}$ – loss of air pressure to overcome the aerodynamic drag force of the air mixture, Pa; $\Delta P_{w,s}$ and $\Delta P_{w,a}$ – air pressure losses due to overcoming the friction force on the surface of the pipeline of the dispersed and air phases of the air mixture, respectively, Pa; $\Delta P_{g,s}$ and $\Delta P_{g,a}$ – air pressure loss to overcome the gravitational force of the dispersed ($F_{g,s}$) and air ($F_{g,a}$) phases of the air mixture, respectively, Pa.

The loss of air pressure ($\Delta P_{a,s}$)_x to overcome the aerodynamic drag force of the air mixture in a cross-section of the pipeline $0 \leq x \leq L_{pip}$ is determined by the equation

$$\Delta(P_{a,s})_x = \frac{c_{as}}{2} \Delta[\rho_{a,x}(u_x - v_x)^2], \quad (2)$$

where c_{as} – dimensionless drag coefficient; $\rho_{a,x}$ – density of the air phase of the air mixture in the selected section of the pipeline, kg/m³; u_x and v_x – velocity of the air and dispersed phases of the air mixture in the selected section of the pipeline, m/s.

The value of the aerodynamic drag coefficient c_{as} from equation (2), is a function of a large number of variables and varies widely: from 0.5 for spherical particles of bulk material to 1.4 for irregularly shaped particles [17]. Obtaining an analytical dependence for this coefficient is an extremely difficult task, so empirical dependencies are usually used in calculations. In [18], the following dependence is given for the developed turbulence regime:

$$c_{as} = 5.31 - 4.88\psi, \quad (3)$$

where ψ – dimensionless sphericity coefficient, which is accepted for pneumatic transportation of rock $0.8 \leq \psi \leq 1$ ($\psi = 1$ corresponds to spherical rock particles $c_{as} = 0.43$).

In the mechanics of two-phase “gas-solid particles” flow, it is accepted [7, 15] that the velocities of the air and dispersed phases as it moves through the PTS pipeline are related to each other through the slip coefficient (relative velocity) of the air mixture phases φ , namely: $\varphi = (u_x - v_x) / u_x \Rightarrow v_x = u_x(1 - \varphi)$. Taking this into account, equation (2) takes the form:

$$\Delta(P_{a,s})_x = \frac{c_{as}\varphi^2}{2} \Delta(\rho_{a,x}u_x^2). \quad (4)$$

The relative velocity coefficient φ characterizes the distribution of velocities in the air and dispersed phases in an air mixture, in which the velocity of dispersed phases is a complex function of many variables, including:

– physical and mechanical properties of dispersed phase particles (size, shape, density, etc.);

- characteristics of the air phase (velocity, turbulence, and viscosity);
- influence of acting forces (drag, gravity, inertia, etc.).

Taking this into account, in most cases, the coefficient φ is determined experimentally for each type of dispersed phase of the air mixture during its transportation in a stable state in suspension.

The loss of air pressure to overcome the friction force on the surface of the pipeline of the dispersed $(\Delta P_{w,s})_x$ and air $(\Delta P_{w,a})_x$ phases of the air mixture in a cross-section of the pipeline $0 \leq x \leq L_{pip}$ is determined as:

$$\Delta(P_{w,s})_x = \frac{\zeta_s}{2} \Delta(\rho_{s,x} v_x^2) = \frac{\zeta_s (1-\varphi)^2}{2} \Delta(\rho_{s,x} u_x^2); \quad (5)$$

$$\Delta(P_{w,a})_x = \frac{\zeta_a}{2} \Delta(\rho_{a,x} u_x^2), \quad (6)$$

where ζ_s and ζ_a – dimensionless coefficients of hydraulic resistance of the dispersed and air phases of the air mixture movement along the pipeline surface, $\rho_{s,x}$ – density of the dispersed phase of the air mixture, kg/m^3 .

The coefficients ζ_s and ζ_a in this mathematical model play the role of coefficients of friction resistance of the air mixture on the pipeline surface. They depend on many factors, such as: type of friction (sliding, rolling); transported material; pipeline surface (material and surface condition). Depending on the transportation conditions, the friction resistance coefficient, for example, of rock on metal, is determined experimentally and can vary in the range from 0.2 to 0.8 and above. In particular, for sandstones with a density ranging from 2.65 t/m^3 to 2.67 t/m^3 , the average friction coefficient on a dry metal surface is $\zeta_s = 0.65$ [19].

The hydraulic resistance coefficient (friction resistance) ζ_a of the air phase of an air mixture in a pipe with a circular cross-section and a hydraulically smooth wall for the region of purely turbulent stabilized flow can be calculated using the Filonenko-Altshul formula [20]:

$$\zeta_a = (1.8 \ln \text{Re} - 1.64)^{-2}, \quad (7)$$

where $\text{Re} = u_1 D_{pip} / \nu$ – Reynolds number; $\nu = 15.06 \cdot 10^{-6} \text{ m}^2/\text{s}$ – kinematic viscosity of air at temperature of 20°C .

Taking into account that

$$u_1 = 4Q_a / (\pi D_{pip}^2),$$

where Q_a – the air flow rate at the beginning of the pipeline (m^3/s), equation (6) looks like:

$$\xi_a = \left(1.8 \ln \frac{4Q_a}{\pi v D_{pip}} - 1.64 \right)^{-2}. \quad (8)$$

Air pressure losses due to overcoming the gravitational forces of the dispersed and air phases of the air mixture $(\Delta P_{g,s})_x$ and $(\Delta P_{g,a})_x$ in a cross-section of the pipeline $0 \leq x \leq L_{pip}$ are determined as:

$$\Delta(P_{g,s})_x = \Delta(\rho_{s,x}x) \varepsilon g \sin \omega; \quad \Delta(P_{g,a})_x = \Delta(\rho_{a,x}x) (1 - \varepsilon) g \sin \omega, \quad (9)$$

where ε – porosity of the elementary volume of the air mixture (dimensionless coefficient of filling of the pipeline cross-section with the dispersed phase of the air mixture); g – acceleration of gravity, m/s^2 .

When transporting an air mixture with dense packing of dispersed phase particles, the porosity of its elementary volume is in the range $0.3 < \varepsilon < 0.7$ [15].

For constant values of $c_{a,s}$, φ , ζ_s , ζ_a , ε for an arbitrary cross-section of the PTS pipeline along the length $0 \leq x \leq L_{pip}$, taking into account equations (2), (4) – (6), in differential form, equality (1) has the following form:

$$\begin{aligned} dP_x = & \frac{c_{as}\varphi^2}{2} d(\rho_{a,x}u_x^2) + \frac{\zeta_s(1-\varphi)^2}{2} d(\rho_{s,x}u_x^2) + \frac{\zeta_a}{2} d(\rho_{a,x}u_x^2) + \\ & + (\varepsilon g \sin \omega) d(\rho_{s,x}x) + (1 - \varepsilon)(g \sin \omega) d(\rho_{a,x}x). \end{aligned}$$

Provided that the dispersed phase of the air mixture is transported in a stable state, its density can be considered a constant value. $\rho_{s,x} \approx \rho_s = \text{const}$. In this case, the last equation can be reduced to the form:

$$\begin{aligned} dP_x = & \frac{1}{2} (c_{as}\varphi^2 + \zeta_a) d(\rho_{a,x}u_x^2) + \frac{\zeta_s\rho_s(1-\varphi)^2}{2} du_x^2 + \\ & + (g \sin \omega) [\varepsilon \rho_s dx + (1 - \varepsilon) d(\rho_{a,x}x)]. \end{aligned} \quad (10)$$

By expanding the differentials and integrating equation (10) along the length of the pipeline (within the range $0 \leq x \leq L_{pip}$), we obtain:

$$\begin{aligned} P_2 - P_1 = & (c_{as}\varphi^2 + \zeta_a) (\rho_{a,2} - \rho_{a,1}) (u_2^2 - u_1^2) + \frac{\zeta_s\rho_s(1-\varphi)^2}{6} + \\ & + [\varepsilon \rho_s + (\rho_{a,2} - \rho_{a,1})(2 - \varepsilon)] L_{pip} g \sin \omega. \end{aligned} \quad (11)$$

The air density $\rho_{a,1}$ from the (11), is found using the Mendeleev - Clapeyron ideal gas equation of state:

$$\rho_{a,1} = P_1 / (RT), \quad (12)$$

where R – gas constant, J/(kg·K); T – temperature, K.

Equation (11) characterizes the relationship between the parameters of the linear movement of the air mixture through a round-section pipeline in its separate sections: horizontal ($\omega = 0$), lifting ($0 < \omega < 90^\circ$), and vertical ($\omega = 90^\circ$).

In many technological processes that use the PTS, the pipeline must be laid by combining different sections: horizontal, ascending, vertical, and inclined. Individual sections of the pipeline are connected to each other by various structural elements: elbows, bends, tees, etc. In this case, the components of hydraulic resistance in equation (11) are two groups:

- friction resistance caused by various types of unevenness and roughness on the surface and characterized by a friction resistance coefficient $\zeta_{a,f}$;
- local hydraulic resistances, which are present in certain sections of the pipeline, in particular, pipe bends in ascending sections, etc., and are characterized by a local resistance coefficient $\zeta_{a,l}$.

Air pressure losses to overcome hydraulic resistance forces in any complex section of a pipeline are inseparable. Despite the fact that local hydraulic resistance acts on a fairly long length of pipeline (with the exception of the end section), this type of resistance is usually considered to be concentrated in a single cross-section. Both coefficients, which are determined experimentally, are summed up as $\zeta_a = \zeta_{a,f} + \zeta_{a,l}$, and air pressure losses are determined as the arithmetic sum of friction losses and local losses [21].

4. Results and discussion

Equation (11) with equations (3), (8), and (12), allows us to determine the main parameters of the air mixture movement in a separate section of a straight pipe with a constant diameter. An important characteristic of pneumatic backfilling equipment is the velocity at which the air mixture leaves the pipeline. This is explained by the possibility of ensuring the highest possible density of the backfilling massif. This characteristic can be obtained by solving equation (11) for the velocity u_2 . As an example, let us consider the transportation of a type of rock – sandstone – along the ascending section of the PTS pipeline with the initial parameters given in Table 1.

As a result of solving equation (11) with respect to velocity u_2 , we obtain a cubic equation whose discriminant is greater than 0. Therefore, the equation has one real root and two complex roots. Figures 2 and 3 show the graphical dependencies of the air phase velocity of the air-fuel mixture at the outlet of the pipeline on the angle of its inclination during the transportation of sand or bulk materials with similar physical and mechanical properties.

For stable transportation of air mixture with $\varphi = 0.4$, the following changes in air leakage velocity from the ascending section of the PTS pipeline are characteristic (Fig. 2):

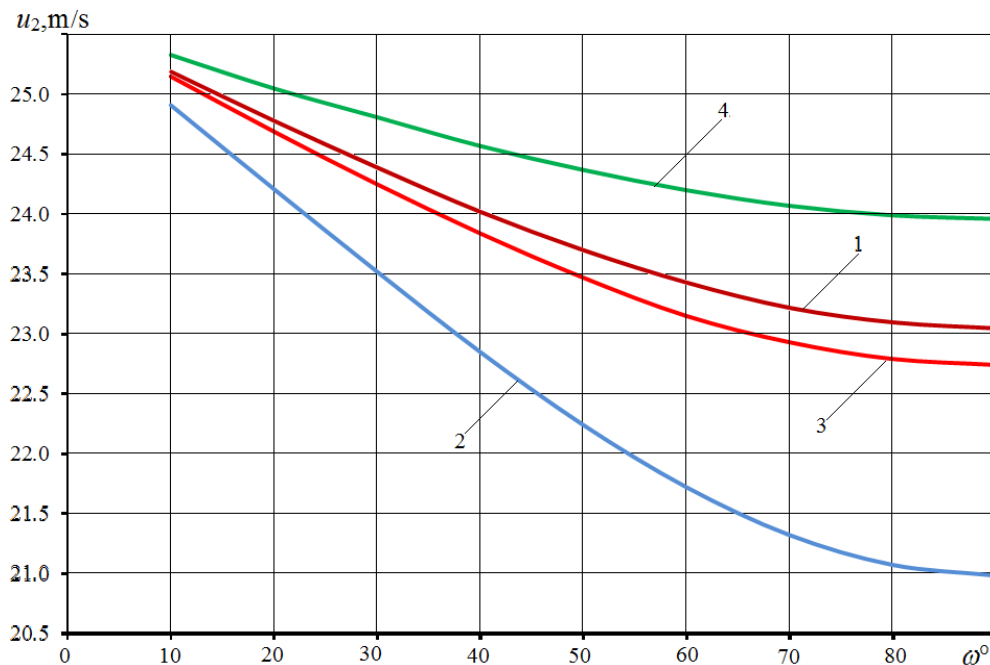
1) A decrease in 1.5 times in the porosity of the air mixture ε causes an increase in the corresponding air velocity u_2 by approximately:

1...4% for pipeline with $L_{pip} = 30$ m (dependencies 1 and 4);

4...8% for pipeline with $L_{pip} = 50$ m (dependencies 2 and 3).

Table 1 – Parameters for calculating the air phase velocity of the air mixture at the outlet of the PTS pipeline

Initial parameters		Variable parameters	
name	value	name	value
Air pressure at inlet (P_1), MPa	0.3	Pipeline length (L_{pip}), m	30; 50
Air temperature at the inlet (T), K	288.15	Porosity of the elementary volume of the air mixture (ε)	0.4; 0.6
Air consumption (Q_a), m ³ /s	0.833		
Air pressure at the outlet (P_2), MPa	0.101330		
Air density at the outlet ($\rho_{a,2}$), kg/m ³	1.2255	Angle of inclination of the pipeline axis to the horizon (ω), °	from 10 to 90
Kinematic viscosity of air (ν), m ² /s	$15.06 \cdot 10^{-6}$		
Hydraulic resistance coefficient (dry friction on metal) of the dispersed phase (ζ_s)	0.65	Phase slip ratio (φ)	0.01; 0.1; 0.3; 0.4
Pipeline diameter (Dm_{pip}), m	0.2		
Air gas constant (R), J/(kg·K)	287.14		
acceleration of gravity (g), m/s ²	9.81		
Aerodynamic drag coefficient ($c_{a,s}$)	0.43		



1 – dependence for $L_{pip} = 30$ m and $\varepsilon = 0.6$; 2 – dependence for $L_{pip} = 50$ m and $\varepsilon = 0.6$;

3 – dependence for $L_{pip} = 50$ m and $\varepsilon = 0.4$; 4 – dependence for $L_{pip} = 30$ m and $\varepsilon = 0.4$

Figure 2 – Dependencies of air velocity u_2 at the outlet of a pipeline with length L_{pip} on its angle of inclination to the horizon ω for an air mixture porosity coefficient $\varphi = 0.4$

2) A decrease in pipeline length by a factor of ~ 1.7 causes an increase in the corresponding air velocity u_2 by approximately:

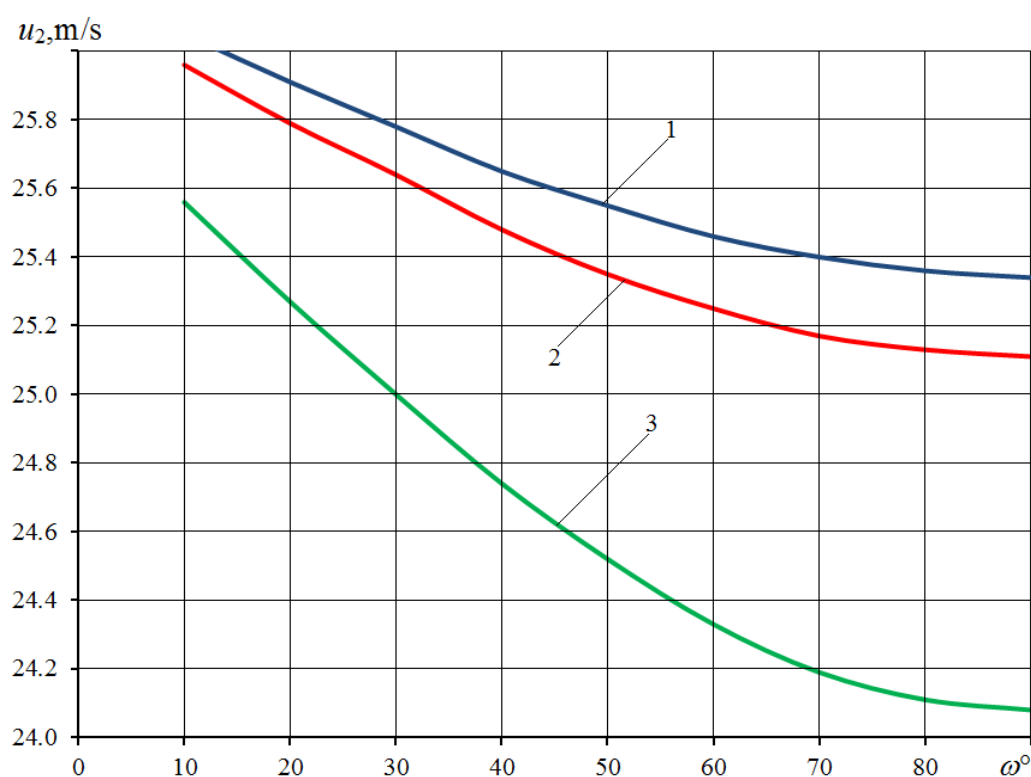
1...9% for the porosity coefficient of the air mixture $\varepsilon = 0.6$ (dependencies 2 and 1);

1...5% for the porosity coefficient of the air mixture $\varepsilon = 0.4$ (dependencies 3 and 4).

For stable transportation of air mixture through a pipeline $L_{pip} = 30$ m with a coefficient $\varepsilon = 0.6$, the following changes in air leakage velocity from the ascending section of the PTS pipeline are characteristic (Fig. 3):

– an increase in the phase slip coefficient in the range $0.02 \leq \varphi \leq 0.1$ causes, depending on the angle of inclination of the pipeline section, a decrease in the corresponding air velocity u_2 by approximately 1% (dependencies 1 and 2);

– an increase in the phase slip coefficient in the range $0.1 \leq \varphi \leq 0.3$ causes a decrease in the corresponding air velocity u_2 by approximately 2...4% (dependencies 2 and 3), depending on the angle of inclination of the pipeline section.



1 – dependence for $\varphi = 0.02$; 2 – dependence for $\varphi = 0.1$; 3 – dependence for $\varphi = 0.3$

Figure 3 – Dependencies of air velocity u_2 at the outlet of a pipeline with length $L_{pip} = 30$ m on its angle of inclination to the horizon ω , taking into account the phase slip coefficient φ for the air mixture porosity coefficient $\varepsilon = 0.6$

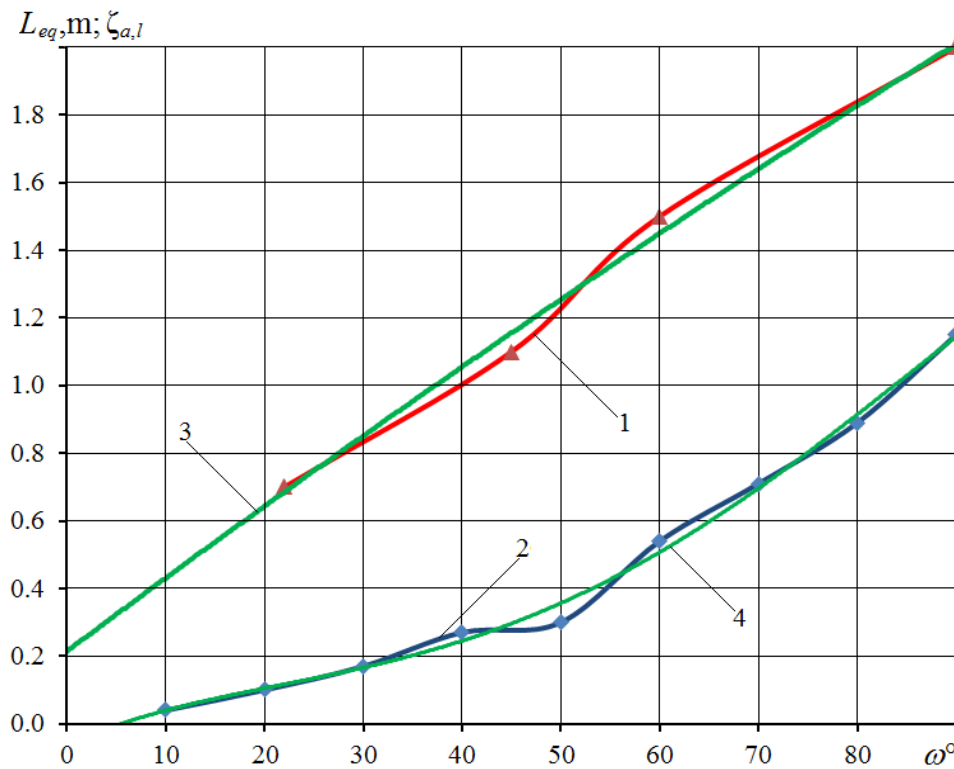
From the dependencies shown in Fig. 2 and Fig. 3, it follows that the decrease in the velocity of the air phase of the air mixture in the ascending section of the PTS pipeline increases with an increase in the following coefficients:

– coefficient of porosity of the elementary volume of the air mixture ε (filling of the pipe cross-section), which can be reduced by shortening the pipe length L_{pip} (Fig.2);

– coefficient of phase slip of the air mixture, which generally needs to be determined separately for each type of dispersed phase of the air mixture (Fig. 3)

For combined sections of the PTS route, when different types of elbows are required to connect the ascending section of the pipeline to its horizontal part, the presence of pipeline inclination angles is taken into account in equation (11) by adding to the total value of the length of the transport pipeline its equivalent length L_{eq} ; and by adding to the total value of the hydraulic resistance the local hydraulic resistances $\zeta_{a,l}$.

In most cases, the values of L_{eq} and $\zeta_{a,l}$ are obtained experimentally and reference data are used. Fig. 4 shows the graphical dependencies of the equivalent pipeline length L_{eq} and the local resistance coefficient $\zeta_{a,l}$ on the angle of inclination of the pipeline ascending section axis to the horizon for transporting air mixture, which are constructed based on the data presented in the works [14, 22].



1 – dependence of the equivalent length of the pipeline L_{eq} on the angle ω ;
2 – dependence of the coefficient $\zeta_{a,l}$ on the angle ω ; 3,4 – trend lines

Figure 4 – Dependencies of the equivalent length of the pipeline L_{eq} and the coefficient $\zeta_{a,l}$ on the angle of inclination of the pipeline elbow ω

According to Fig. 4, the functional dependencies $L_{eq} = f(\omega)$ and $\zeta_{a,l} = v(\omega)$ have polynomial characteristics, the approximation of which with confidence $R^2 \rightarrow 1$ shows that

$$L_{eq} = -2 \cdot 10^{-5} \omega^2 + 0.0219 \omega + 0.2149; \quad (13)$$

$$\zeta_{a,l} = -3 \cdot 10^{-8} \omega^4 + 7 \cdot 10^{-6} \omega^3 - 4 \cdot 10^{-4} \omega^2 + 0.013 \omega - 0.0611. \quad (14)$$

Taking into account these dependencies, the components of equation (11) according to the law of additivity during transportation of the air mixture through a pipeline with combined sections have the following form:

$$L_{pip} = \sum_{j=1}^{\chi} L_{pip,j} + \sum_{i=1}^{\varpi} L_{eq,i}; \quad (15)$$

$$\zeta_a = \sum_{j=1}^{\chi} (\zeta_{a,f})_j + \sum_{i=1}^{\varpi} (\zeta_{a,l})_i, \quad (16)$$

where $L_{pip,j}$ – length of a separate straight section of pipeline with a constant diameter, m; χ – number of straight sections of pipeline; $L_{eq,i}$ – equivalent length of the connecting elbow of the pipeline, m; ϖ – number of connecting elbows; $(\zeta_{a,f})_j$ – friction resistance coefficient of a separate straight section of a pipeline; $(\zeta_{a,l})_i$ – local hydraulic resistance coefficient of a single elbow.

The values $L_{pip,j}$ and $(\zeta_{a,f})_j$ are specified when calculating the PTS route at the design stage. To determine the values $L_{eq,i}$ and $(\zeta_{a,l})_i$ in engineering calculations, dependencies (13) and (14) are used.

The developed method for calculating the parameters of air mixture transportation for an arbitrary scheme of individual sections of the PTS pipeline allows:

- calculating the parameters of rock transportation in the PTS, which has a different transportation scheme, including ascending sections and elbows;
- determine the rational parameters (pressure and flow rate) of compressed air required for the effective use of PTS in solving technological problems.

The scientific novelty of the research on the movement of air mixture in the PTS with ascending sections of transport pipeline lies in obtaining:

- a determining equation for the movement of air mixture through the PTS pipeline with an arbitrary trajectory (including ascending sections), taking into account the number of straight sections of the pipeline ($j = 1 \dots \chi$), the presence and number of ascending elements (elbows) (ω_i , $i = 1 \dots \varpi$)
- dependencies for determining the total values of the length of the PTS transport pipeline and the local hydraulic resistance coefficient depending on the presence and number of ascending sections of the pipeline with angles ω_i , $i = 1 \dots \varpi$;
- the relationship between the parameters of compressed air supplied to the PTS (P_1 , T , u_1), the characteristics of the dispersed and air phases of the air mixture (ρ_s , c_{as} , ζ_s , ζ_a), technological (φ , ε) and design parameters (L_{pip} , D_{pip} , ω) of the PTS for stable transportation of the air mixture in a suspended state.

The use of these dependencies in engineering methods for calculating pneumatic conveying systems of arbitrary configuration will allow determining their rational

parameters, primarily in terms of ensuring the supply of compressed air for transporting bulk materials with a given productivity over the required transport distance. This will make it possible to expand the scope of application of the pneumatic method of transporting bulk materials in various industries, especially in mining and metallurgical enterprises when disposing of waste from the extraction and processing of minerals in the mined-out space of mines.

5. Conclusions

As a result of the research, methods for calculating the mechanics of two-phase “gas – solid particles” flows in pipeline transport systems were further developed by taking into account the characteristics of resistance components, primarily ascending sections, in the determining equation for calculating the parameters of air mixture flow in transport systems. The influence of resistance components on the change in the velocity of the air phase of the air mixture, which determines the ability to transport the dispersed phase of the air mixture over the required distance with the required productivity, is shown.

The presence in the transport pipeline of a single section of the horizontal part of the pipeline ascending at a certain angle, followed by straight-line transportation of the air mixture, causes an increase in the polynomial dependence of the local hydraulic resistance coefficient of this section on the angle of inclination. For several ascending sections, their total hydraulic resistance coefficient is found using an additive method, taking into account the values of similar coefficients calculated for the corresponding angles of inclination.

Each ascending section of the PTS pipeline necessitates an increase in the calculated transportation distance of the air mixture by a certain equivalent length of the same pipeline, which varies according to a polynomial dependence on the angle of inclination. The total calculated distance of pneumatic transportation of the dispersed phase of the air mixture (rock) through the PTS pipeline depends on the number of ascending sections and their inclination angle and is found using the additivity method.

The results of the research can be used in the design and improvement of the PTSs that have ascending sections of transport pipeline. The application of these results in engineering calculations of similar systems will allow determining the necessary parameters of compressed air for its supply to the PTS. This will enable the transportation of bulk materials (rock) with different physical and mechanical properties at a specified rate over the required distance and with the necessary velocity of the air mixture leaving the pipeline. These factors will increase the efficiency of PTS use in various technological processes at mining and metallurgical enterprises, in particular, increase the percentage of backfilling the mined-out space of mines with waste from the extraction and processing of minerals.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Bini, C, Maleci, L and Wahsha, M. (2017), "Mine Waste: Assessment of Environmental Contamination and Restoration", *Assessment, Restoration and Reclamation of Mining Influenced Soils*, Academic Press, pp. 89–134. <http://dx.doi.org/10.1016/b978-0-12-809588-1.00004-9>
2. Petlovanyi, MV, Malashkevych, DS and Sai, KS. (2020), "The new approach to creating progressive and low-waste mining technology for thin coal seams", *Journal of Geology, Geography and Geoecology*, vol. 29, no. 4, pp. 765–775. <http://dx.doi.org/10.15421/112069>
3. Petlovanyi, MV, Malashkevych, DS, Sai, KS and Stoliarska, OV. (2023), "Ecological-economic aspects of mining thin coal seams in the Western Donbas", *Journal of Geology, Geography and Geoecology*, vol. 32, no. 3, pp. 569–580. <http://dx.doi.org/10.15421/112351>
4. Liu, H. (2003), *Pipeline Engineering*, CRC Press, <https://doi.org/10.1201/9780203506684>
5. Zaporozhets, O. and Volodin, S. (2024), "Parametric synthesis of a mechatronic system for pneumatic conveying of bulk products", *Scientific Works of National University of Food Technologies*, vol. 30, no. 4, pp. 88–98. <http://doi.org/10.24263/2225-2924-2024-30-4-8>
6. Zhou, J., Ba, H., Yan, X. and Shangguan, L. (2023), "Solid friction coefficient in a horizontal straight pipe of pneumatic conveying", *Chemical Engineering Research and Design*, vol. 196, pp. 577–587, <https://doi.org/10.1016/j.cherd.2023.07.001>
7. Poturaev, V.N., Bulat, A.F., Voloshin, A.I., Ponomarenko, S.N. and Voloshin, A.A. (2001), *Mekhanika vibratsiynno-pnevmatychnykh mashyn ezhektornoho typu* [Mechanics of vibration-pneumatic machines of the ejector type], Naukova Dumka, Kyiv, Ukraine.
8. Voloshyn, O.I., Koval O.I. and Ponomarenko, S.M. (2011), "Use of ejector stowage machines in mining technologies", *Coal of Ukraine*, no. 4, pp. 40–44.
9. Qi, Y., Lu, H., Du, H., Guo, X. and Liu, H. (2024), "Effect of resistance components on solid mass flow rate of the pneumatic conveying system", *Chemical Engineering Research and Design*, vol. 212, pp. 536–545. <https://doi.org/10.1016/j.cherd.2024.11.021>
10. Khodjiev, M., Abbasov, I. and Karimov, J. (2021), "Influence of Local Resistance on Pressure and Speed Changes in Expanded Pneumatic Conveying", *E3S Web of Conferences, "2nd International Conference on Energetics, Civil and Agricultural Engineering (ICECAE 2021)"*, vol. 304, 03016. <http://dx.doi.org/10.1051/e3sconf/202130403016>
11. Tripathi, NM., Portnikov, D., Levy, A. and Kalman, H. (2019). "Bend pressure drop in horizontal and vertical dilute phase pneumatic conveying systems", *Chemical Engineering Science*, vol. 209, 115228, <http://doi.org/10.1016/j.ces.2019.115228>
12. Carpinlioglu, MÖ., Özbelge, TA. and Oruc, V. (2002), "Flow frictional resistance in pneumatic conveying of solid particles through inclined lines", *Powder Technology*, vol. 125, issue 2–3, pp. 292–297, [http://doi.org/10.1016/s0032-5910\(01\)00517-4](http://doi.org/10.1016/s0032-5910(01)00517-4)
13. Gushchin, V. M., and Gushchin, O. V. (2010), "Analysis of modes of movement of air mixtures in a pneumatic transport pipeline", *Visnyk Donbaskoi Derzhavnoi Mashynobudivnoi Akademii*, no.1(18), pp. 78–83.
14. Klyachko, L.S., Odelsky, E.H. and Khrustalev, B.M. (1984), *Pnevmaticheskii transport sypuchikh materialov* [Pneumatic transport of bulk materials], Nauka i tekhnologii, Minsk, Belarusian.
15. Bulat, A.F. and Voloshin, A.I. (2019), *Mekhanika dvofaznykh potokiv. Tom 3. Metody rozrakhunku dvofaznykh potokiv u truboprovodnykh systemakh* [Mechanics of two-phase flows. Vol. 3. Methods for calculating two-phase flows in pipeline systems], in Voloshyn, O.I. (ed.), Naukova dumka, Kyiv, Ukraine.
16. Voloshin, O.I. and Ponomarenko, S.M. (2020), *Mekhanika dvofaznykh potokiv. Tom 4. Mekhanika dvofaznykh potokiv u pnevmotransportnykh systemakh ezhektornoho typu* [Mechanics of two-phase flows. Vol. 4. Mechanics of two-phase flows in pneumatic transport systems of the ejector type], in Voloshyn, O.I. (ed.), Naukova dumka, Kyiv, Ukraine.
17. Yarmolenko, G.Z. (1977), *Pnevmaticheskiye turbiny i struynnye apparaty gornykh mashin* [Pneumatic turbines and jet devices of mining machines], Nedra, Moscow, Russia.
18. Razumov, I.M. (1972), *Psevdoozhizhneniye i pnevmotransport sypuchikh materialov. Izdaniye vtoroye, dopolnenoye i pererabannoye* [Pseudo-liquefaction and pneumatic transport of bulk materials. Second edition, supplemented and revised], Khimiya, Moscow, Russia.
19. Svitlyi, Yu.G. and Biletsky, V.S. (2009), *Hidravlichnyy transport (monohrafiya)* [Hydraulic transport (monograph)], Skhidnyy vydavnychyy dim, Donetsk'ke viddilennya NTSH «Redaktsiya hirnychoyi entsyklopediyi», Donetsk, Ukraine.
20. Altshul, A.D. (1970), *Hidravlichni opory* [Hydraulic resistances]. Nedra, Moscow, Soviet Union.
21. Idelchik, I.E. (1975), *Spravochnik po gidravlicheskim soprotivleniyam* [Handbook of hydraulic resistances], Mashinostroyeniye, Moscow, SU.
22. Gneushev, V.O. (2010), *Ventilyatsiya i pnevmatichnyy transport. Navch. posibnyk* [Ventilation and pneumatic transport. Textbook], Rivne, NUVHP, Ukraine.

About the authors

Ponomarenko Serhii, Doctor of Technical Sciences, Senior Researcher, Senior Researcher in Department of Mechanics of Vibratory Transporting Systems and Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, ponomarenko@ua.fm (**Corresponding author**), ORCID **0000-0003-1346-7008**

Riabtsev Oleh, Candidate of Technical Sciences (Ph.D), Senior Researcher, Senior Researcher in Department of Mechanics of Vibratory Transporting Systems and Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, o.ryabtsev1973@gmail.com, ORCID **0000-0002-9022-4328**

Kabakova Liudmyla, Candidate of Technical Sciences (Ph.D), Senior Researcher, Senior Researcher in Department of Mechanics of Vibratory Transporting Systems and Complexes, M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine (IGTM of the NAS of Ukraine), Dnipro, Ukraine, lyudmila1520@gmail.com, ORCID **0000-0001-9356-2050**

УРАХУВАННЯ ПІДЙОМНИХ ДІЛЯНОК ТРУБОПРОВОДУ ПІД ЧАС РУХУ ГІРСЬКОЇ ПОРОДИ В СИСТЕМАХ ПНЕВМОТРАНСПОРТУВАННЯ

Пономаренко С., Рябцев О., Кабакова Л.

Анотація. Залишення відходів видобутку корисних копалин у шахті та використання їх для закладки виробленого простору спрямоване на розв'язання як екологічних проблем, так і гірничотехнічних завдань, насамперед, управління гірським тиском. Одним із напрямків реалізації вирішення цих завдань є застосування пневматичного способу закладки, який забезпечує можливість досягнення високої щільності закладувального масиву. Предметом досліджень є фізичні процеси, що відбуваються в трубопровідних пневмотранспортних системах при наявності в них ділянок підйому. Темою роботи є оцінка резистентності елементів транспортного трубопроводу, що має підйомні ділянки, до руху аеросуміші та вплив кута підйому на характеристики потоку аеросуміші на виході з пневмотранспортної системи. Метою роботи є отримання визначального рівняння, що описує рух аеросуміші трубопроводом сталого діаметру з урахуванням наявності місцевих гідравлічних опорів, які присутні на окремих ділянках трубопроводу та змінюють напрямок руху аеросуміші. Наявність у визначальному рівнянні кута нахилу осі транспортного трубопроводу до горизонту $\omega > 0^\circ$ дозволяє адаптувати це рівняння до умов транспортування в горизонтальному ($\omega = 0^\circ$) або вертикальному ($\omega = 90^\circ$) напрямку. Методологія проведення роботи полягає в застосуванні феноменологічного підходу до визначення сил опору руху двофазного потоку «газ – тверді частинки» в циліндричному трубопроводі. Вплив резистентних характеристик прямолінійних та поворотних елементів трубопроводу на технологічні та конструктивні параметри пневмотранспортної системи враховано адитивністю цих параметрів для кожного окремого елементу. Сферою застосування отриманих результатів є розвиток наукових основ теорії руху двофазних потоків «газ – тверді частинки» в трубопровідних системах пневмотранспорту дисперсних матеріалів в щільній фазі. Реалізація результатів досліджень в інженерних методах розрахунку існуючих і нових пневмотранспортних систем дозволить підвищити ефективність їх використання в технологічних процесах переміщення дисперсних матеріалів на підприємствах гірничо-металургійного комплексу та в інших галузях промисловості.

Ключові слова: пневмотранспортна система, коефіцієнт опору, транспортний трубопровід, підйомна ділянка, аеросуміш.