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PATTERNS OF AIR MIXTURE MOVEMENT IN THE OPERATING AREA FOR THE ANNULAR EJECTOR OF PNEUMATIC TRANSPORTATION SYSTEM

Purpose. To establish the regularities of two-phase flow of "gas-solid particles" in the operating area of an annular ejector where the following processes take place: air mixture ejecting, compressed air outflow from the ejector nozzle, air mixture flows mixing in the transport pipeline. In the work, the velocity distribution is also examined for dispersed phase and air phase of air mixture during its loading and accelerating in the transport pipeline of the pneumatic transport system.

Methodology. The research is based on the fundamental approaches of mass point dynamics, aerodynamics, the theory of jet flows and iteration methods of numerical solution of equations.

Findings. The mechanics of the air mixture flow under the ejection and aerodynamic force in the operating area of an annular ejector and at the beginning of transport pipeline is analyzed using the method of iterations. The impact of air mixture flow in the operating area of an annular ejector on energy performance of the pneumatic transport system is evaluated.

Originality. The originality is that, for the first time, the regularities describing two-phase "gas–solid particles" flow at the loading area of the pneumatic transport system with an annular ejector have been obtained. This made it possible to characterize the velocity distribution of the dispersed and air phases of the air mixture during their loading and aerodynamic acceleration in the transport pipeline. Also, an innovative approach to the effectiveness of the use of pipeline pneumatic transport is the assessment of the energy indicators of the use of ejector-type pneumatic transport equipment depending on the rate of compressed air outflow from the ejector.

Practical value. The implementation of the results in the modernization of existing and in the creation of new pneumatic transport systems with an annular ejector makes it possible to increase the efficiency of their use in the technological processes of moving dispersed materials at mining and metallurgical enterprises and in other areas of technology.

Keywords: *pneumatic transportation system, air mixture, annular ejector, transport pipeline*

Introduction. Pipeline and pneumatic transports, in particular, are widely used in various sectors of national economies [1]. Stationary and mobile pneumatic transport systems of domestic and foreign production are used in a wide range of various technological processes. The advantages of pneumatic transportation of dispersed materials are well known and make the pneumatic transportation the most attractive for use in limited production conditions without harmful effects on the environment. The main disadvantages of this type of transportation include the high specific electricity consumption (up to 4–10 kWh/t) for the movement of dispersed material and the cost of demolition of pipelines and equipment; these costs can reach 50 and 30 % of the cost of transportation, respectively [2, 3].

In this paper, the object of the research is ejector-type pneumatic transport equipment, which, due to its design features, makes their use more effective as shop pneumatic transport compared to other types of pneumatic transport equipment [4].

The efficiency of using ejector pneumatic transport systems (PTS) at mining and metallurgical enterprises for transporting the dispersed materials through the pipeline depends on the power intensity of the processes of loading and moving the air mixture under the ejection and aerodynamic force. Reducing the power intensity of these processes is a relevant task that needs the research on a physical picture of the two-phase "gas–solid particles" flow with minimal possible energy losses of the carrier flow.

Literature review. A characteristic feature of the air mixture flow in the ejector-type PTS is the presence of continuous turbulent disturbances caused by several separate flows: the ejected total flow of dispersed and air phases of the air mixture and the ejecting flow of compressed air. A large number of foreign and Ukrainian scientists have been engaged in fundamental and experimental studies on the mechanics of two-phase "gas–solid particles" flows. In particular, in the studies by A. Ye. Smoldyrev, I. M. Razumov and L. S. Klyachko a significant number of the problems of pneumatic transport of dispersed materials by pipeline systems is considered. However, the peculiarities of dispersed material loading by ejection and the interaction of turbulent flows at the beginning of the pipeline have not been sufficiently investigated. The results of studies on turbulent mixing of ejecting and ejected flows of homogeneous and heterogeneous gases are presented quite fully and in detail in works [5, 6], but these works do not take into account the presence of a dispersed phase of the air mixture in the mixing zone and its influence on the general characteristics of the flow. So, the regularities of pipeline pneumatic transportation of dispersed materials and turbulent mixing of air jets obtained in these works cannot fully describe the regularities of the air mixture flow in the operating area of the PTS annular ejector.

Status of the issue. The use of complex nonlinear Navier-Stokes and Reynolds equations [7], related to the fundamental scientific principles in the study on turbulence, in the practice of studies on air mixture flow by ejector PTS raises many questions and uncertainties. In this regard, these equations are not used widely, and the mathematical description of air mixture flow under the joint action of ejection and aerodynamic force is an urgent task for the development of science and technology.

Purpose. The purpose of this work is to establish the regularities of movement under the ejection and aerodynamic force of the two-phase "gas–solid particles" flow in operating area of the PTS annular ejector. In accordance with the set goal, to determine the nature of distribution of the velocities of dispersed and air phases of air mixture along the horizontal axis of transport pipeline in the zone of air mixture loading and acceleration in the PTS. In addition, to analyze the effect of changing the rate of compressed air leakage from the ejector on the energy performance of the PTS.

Methods. To obtain a qualitative characteristic of the velocity distribution of dispersed and air phases of air mixture along the horizontal axis of the operating area of an annular ejector, the fundamental approaches are used of mass point dynamics, aerodynamics and the theory of jet flows by the iterative method of the numerical solution of the transcendental equations describing the mechanics of the two-phase "gas–solid particles" flow in the operating area of an annular ejector. To carry out the evaluation of the impact of the change in the rate of leakage of compressed air from the ejector on the energy performance of the PTS, the method of iterations is used.

Results. The kinematics of pneumatic transportation of dispersed material through a pipeline is much more complicated than the air mixture flow in a space between two parallel walls [8]. But the basic nature of the flow of air mixture phases along and across the axis of the pipeline is well described within the framework of a plane problem [2, 9]. In addition, in the analytical solution of most spatial problems related to the turbulent mixing of single phases of air mixture, it is generally accepted to consider a one-dimensional flow of an air mixture with parameters averaged over the cross section [7]. Taking this into account and assuming that the solid phase of the two-phase "gas–solid particles" flow is a lump medium consisting of homogeneous solid particles with a density of ρ_2, let us consider an analytical representation of the mechanics of air mixture flow along a horizontal pipeline for the plane problem, according to the calculation scheme of its movement, the general view of which is shown in Fig. 1. Here: *1* – annular ejector; *2* – particles of dispersed material; *3* – transport pipeline; *D* – the diameter of the transport pipeline; *h* – the width of the annular gap of the ejector nozzle device; *d* – wall thickness of the annular shall of the ejector nozzle device; *f* – the angle of expansion of the ejecting air flow; *L* – the length of stabilization section of the air mixture; *xOy* – rectangular coordinate system; I, II, III – air mixture flow zones; *C* – conical surface top of interaction of the ejected and ejecting air flow; *AA* and *MM* – cross-sections of operating area of annular ejector; ρ_{I}, ρ_{II} and ρ_{III} – densities of the ejected, ejecting and mixed flows of air phase of the air mixture; $\bar{u}_{\mathrm{I}}$, $\bar{u}_{\mathrm{II}}$ and $\bar{u}_{\mathrm{III}}$ – averaged over the cross-section velocities of the ejected, ejecting and mixed flow of air phase of the air mixture.

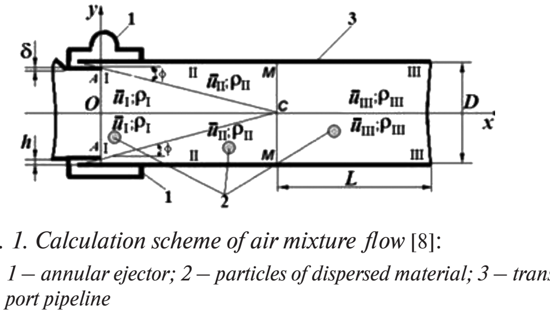

Fig. 1. Calculation scheme of air mixture flow [8]:

1 – annular ejector; 2 – particles of dispersed material; 3 – transport pipeline

The following zones are conditionally allocated on the calculation scheme of air mixture flow: I – ejected air mixture flow (conventional cone with top at point *C* and base located at cross-section *AA*); II – ejecting flow of compressed air (a conventional hollow cylinder with a base of cross-section *MM*, inside which there is a conventional cone of the ejected air mixture flow); III – mixed air mixture flow.

Assuming that the air mixture flow relatively to the axis of the transport pipeline is described by function $f(x) = D/2 - h - \delta - x/\mathrm{ctg}\,\phi$, conditional boundaries of the distribution of the air mixture flow in the operating area of the annular ejector (Fig. 1) has the form [10]

$$0 \le x \le (D/2 - h - \delta)\,\mathrm{ctg}\,\phi; \quad -f(x) \le y \le f(x),$$

for zone I, where a material particle moves under the gravity and air ejected from the atmosphere;

$$0 \le x \le (D/2 - h - \delta)\,\mathrm{ctg}\,\phi; \quad -D/2 \le y \le -f(x),$$

and $f(x) \le y \le D/2$ for zone II, where a material particle moves under the gravity and ejecting compressed air;

$$(D/2 - h - \delta)\,\mathrm{ctg}\,\phi \le x \le L; \quad -D/2 \le y \le D/2,$$

for zone III, where a material particle moves under the gravity and mixed air flow.

According to the fundamental science of the movement of a two-phase "gas–solid particles" flow, a separate particle of solid phase of air mixture in the PTS pipeline is affected by the following forces: gravity; aerodynamic; Magnus-Zhukovskyi and Archimedes forces; interphase viscous friction, which is determined by the law of Stokes, Safman and friction [9, 11].

Taking into account the fact that the Safman force acts only on very small particles of the solid phase of the air mixture, and the Magnus-Zhukovsky lifting force depends on the angular velocity of the particles, in most cases these forces are not taken into account in the theory of pipeline pneumatic transport. Another feature of engineering calculations of movement of a loose material single particle in the air flow is the neglect of the frictional forces of the particle with the walls of the pipeline and with other particles of solid phase of the air mixture.

The density of lump types of loose materials transported by the PTS is 1200–4700 kg/m^3 and depends on the composition, type and degree of metamorphism. Then the ratio of densities of air phase and solid phase of the air mixture, and therefore the Archimedes force, during the transportation of large particles of solid phase of the air mixture can be neglected.

Based on this and using the main equation of the dynamics of mass point from [10] for the analysis of the dynamic state of the solid phase of the two-phase "gas–solid particles" flow in the zones of air mixture flow i = I–III (Fig. 1) under the ejection and aerodynamic force in *xOy* coordinates, the following system of equations is obtained

$$\ln\left|\frac{2\mu_x A_i \bar{v}_{x,i} - 2\mu_x A_i \bar{u}_i - B_i - \sqrt{4\mu_x A_i B_i + B_i^2}}{2\mu_x A_i \bar{v}_{x,i} - 2\mu_x A_i \bar{u}_i - B_i + \sqrt{4\mu_x A_i B_i + B_i^2}} \times \right.$$
$$\left. \times \frac{2\mu_x A_i \bar{v}_{0,x} - 2\mu_x A_i \bar{u}_i\big|_{t_i=0} - B_i + \sqrt{4\mu_x A_i B_i + B_i^2}}{2\mu_x A_i \bar{v}_{0,x} - 2\mu_x A_i \bar{u}_i\big|_{t_i=0} - B_i - \sqrt{4\mu_x A_i B_i + B_i^2}}\right| = \qquad (1)$$
$$= t_i\sqrt{4\mu_x A_i B_i + B_i^2}, \quad (i = I,\ II);$$

$$\ln\left|\frac{2\mu_y A_i\bar{v}_{y,i}-2\mu_y A_i\bar{u}_i-B_i-\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}{2\mu_y A_i\bar{v}_{y,i}-2\mu_y A_i\bar{u}_i-B_i+\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}\times\right.$$
$$\left.\times\frac{2\mu_y A_i\bar{v}_{0,y}-2\mu_y A_i\left.\bar{u}_i\right|_{t_i=0}-B_i+\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}{2\mu_y A_i\bar{v}_{0,y}-2\mu_y A_i\left.\bar{u}_i\right|_{t_i=0}-B_i-\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}\right|=$$
$$=t_i\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2},\quad\left(i\ =\ \mathrm{I,\ II}\right);\tag{2}$$

$$\ln\left|\frac{2\mu_x A_i\bar{v}_{x,i}-2\mu_x A_i\bar{u}_i-B_i-\sqrt{4\mu_x A_i B_i+B_i^2}}{2\mu_x A_i\bar{v}_{x,i}-2\mu_x A_i\bar{u}_i-B_i+\sqrt{4\mu_x A_i B_i+B_i^2}}\times\right.$$
$$\left.\times\frac{2\mu_x A_i\bar{v}_{x,i-1}-2\mu_x A_i\left.\bar{u}_i\right|_{t=t_{i-1}}-B_i+\sqrt{4\mu_x A_i B_i+B_i^2}}{2\mu_x A_i\bar{v}_{x,i-1}-2\mu_x A_i\left.\bar{u}_i\right|_{t=t_{i-1}}-B_i-\sqrt{4\mu_x A_i B_i+B_i^2}}\right|=$$
$$=\left(t_i-t_{i-1}\right)\sqrt{4\mu_x A_i B_i+B_i^2},\quad\left(i\ =\ III\right);\tag{3}$$

$$\ln\left|\frac{2\mu_y A_i\bar{v}_{y,i}-2\mu_y A_i\bar{u}_i-B_i-\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}{2\mu_y A_i\bar{v}_{y,i}-2\mu_y A_i\bar{u}_i-B_i+\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}\times\right.$$
$$\left.\times\frac{2\mu_y A_i\bar{v}_{y,i\text{-}1}-2\mu_y A_i\left.\bar{u}_i\right|_{t=t_{i-1}}-B_i+\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}{2\mu_y A_i\bar{v}_{y,i\text{-}1}-2\mu_y A_i\left.\bar{u}_i\right|_{t=t_{i-1}}-B_i-\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2}}\right|=$$
$$=\left(t_i-t_{i-1}\right)\sqrt{4\mu_y A_i\left(B_i+g\right)+B_i^2},\quad\left(i\ =\ III\right),\tag{4}$$

where μ_x and μy are dimensionless front resistance and lift coefficients (functions of Reynolds number and angle of attack), which are determined experimentally; $A_i=S\dfrac{\rho_i}{2m}$; $B_i=3\pi\nu\dfrac{\rho_i}{m}$ (S is the area of the streamlined surface of the particle, m^2; ρ_i is density of the air phase of the air mixture, kg/m^3; m is mass of an individual particle of the solid phase of air mixture, kg; $\pi = 3.14$; ν is kinematic viscosity of air, m^2/s); $\bar{v}_{x,i}$ and $\bar{v}_{y,i}$ are horizontal and vertical components of the cross-section averaged velocity of a material particle $\bar{v}_i$, m/s; $\bar{u}_{x,i}$ and $\bar{u}_{y,i}$ are horizontal and vertical components of the cross-section averaged velocity of air flow $\bar{u}_i$, m/s; $g = 9.81$ m/s^2 is free fall acceleration; t_i is time of particle movement, s.

The cross-section averaged velocities of air flow $\bar{u}_i$ (i = I–III) are related by the following system of equations [4, 10]

$$\left.\bar{u}_{\mathrm{I}}\right|_{t=0}=0.5\left.\bar{u}_{\mathrm{II}}\right|_{t=0}\left(1-\chi\right)\mathrm{tg}\varphi;\tag{5}$$
$$\left.\bar{u}_{\mathrm{I}}\right|_{t=t_1}=\left.\bar{u}_{\mathrm{II}}\right|_{t=t_1}\Big/\left(1+3\chi\right);\tag{6}$$
$$\left.\bar{u}_{\mathrm{III}}\right|_{t=t_{\mathrm{II}}}=\left.\bar{u}_{\mathrm{II}}\right|_{t=t_{\mathrm{II}}}\left[1-0.5\chi\left(1+\chi\,\mathrm{tg}\varphi\right)\right];\tag{7}$$
$$\left.\bar{u}_{\mathrm{III}}\right|_{t=t_{\mathrm{III}}}=0.5\left.\bar{u}_{\mathrm{II}}\right|_{t=t_{\mathrm{III}}}\left[1-0.5\chi\left(1+\chi\,\mathrm{tg}\varphi\right)\right]\sqrt{0.15+0.85/\left(1-\chi\right)},\tag{8}$$

where χ is dimensionless coefficient of air flow energy dissipation, which is from 0.05 to 0.3 and depends on the design characteristics of the ejector and its connection with the transport pipeline.

The expansion angle of ejecting air flow f for the structural scheme (Fig. 1) of the annular ejector is the angle of local interaction of ejecting and ejected air flows, which plays a significant role in determining the loss of kinetic energy in the process of mixing these flows [4].

Taking into account the insignificant length of the corresponding zones of the air mixture flow for each stage of its movement, it can be assumed that $\bar{u}_i\cong\mathrm{const}$ and $\rho_i \cong$ const (i = I–III).

Taking into account the axiality of the surface of the tangential discontinuity of the ejected and ejecting air flows along the 0x axis (Fig. 1), it is the following $x_{\mathrm{I}} = x_{\mathrm{II}}$; $t_{\mathrm{I}} = t_{\mathrm{II}}$. At the moment of time $t_i = 0$ (i = I, II) the following equations can be written

$$\left.\bar{v}_{x,i}\right|_{t_i=0}=\bar{v}_{0,x};\quad\left.\bar{v}_{y,i}\right|_{t_i=0}=\bar{v}_{0,y},$$

where $\bar{v}_{0,x}$ and $\bar{v}_{0,y}$ are projections on the corresponding coordinate axes of the cross-section averaged supply velocity $\bar{v}_0$ of the dispersed phase of the air mixture in the PTS, which is determined by the loading method of the transported material: gravitational, mechanical, vibro-aerodynamic materials, etc.

The system of equations (1–4), which describes the movement of a single particle of the solid phase of the air mixture, qualitatively assesses the mechanics of the air mixture flow during its loading and aerodynamic acceleration in the operating area of the PTS annular ejector (i = I–III). This estimate is based on taking into account the characteristics of two parallel processes: ejection (ρ_i; $\bar{u}_i$; ϕ and χ) and aerodynamic transport (m; $\bar{v}_i$; S; μ_x and μ_y).

To obtain a quantitative characteristic of mechanics of discrete phase flow of the air mixture during its loading and aerodynamic acceleration in the operating area of the PTS annular ejector, it is necessary to take into account the particle size distribution and physicochemical properties of the transported material. This is due to the fact that each individual solid particle has its own numerical parameters of movement, but the general nature of the air mixture flow is unchanged and subject to the same laws.

The results of solving the transcendental equations (1–4) by iteration method and the regularities of the movement velocities distribution of the air and dispersed phase of the air mixture in the operating zone of the annular ejector are shown in Fig. 2.

Here: *1, 2* – $\bar{u}_i$, *3, 4* – $\bar{v}_i$. The averaged air mixture phase velocities during its movement in zones i = I–III are: velocity of the air phase $\bar{u}_i$ in accordance with equations (5–8); velocity of the dispersed phase $\bar{v}_i=\sqrt{\bar{v}_{x,i}^2+\bar{v}_{y,i}^2}$. In addition, we suppose that the time of movement of a dispersed phase particle is equal to absolute value of the ratio of the distance traveled to the corresponding flight velocity.

To build the dependencies shown in Fig. 2, calculations were carried out with the initial conditions:

- in II (for $0\le x\le(D/2-h-\delta)\,\mathrm{ctg}\,\phi$ and $-D/2\le y\le -f(x)$) and III zones (Fig. 1) the movement of a separate spherical particle of rock (density $\rho_2 = 2$ t/m^3, diameter $d = 0.04$ m, volume $V = 3.35\cdot10^{-5}$ m^3, area of the streamlined surface $S =$ $= 5\cdot10^{-3}$ m^2 and mass $m = 0.067$ kg, $\mu_x = \mu_y = 0.4$) is considered;
- PTS with an annular ejector has the following characteristics: $D = 0.2$ m, $h = \delta = 2$ mm, $L = 1$ m (Fig. 1), ejector flow rate $\chi = 0.1$;
- compressed air (ejecting flow) used for transportation has following parameters: air pressure $\left.P_{\mathrm{II}}\right|_{t=0}=0.2$ MPa, temperature $T_{\mathrm{II}} = T_{\mathrm{I}} = T_{\mathrm{III}} = 290$ K, universal gas constant $R =$ $= 287.14$ J/(kg · K), density (according to the Mendeleev-Clapeyron equation) $\left.\rho_{\mathrm{II}}\right|_{t=0}=2.4$ kg/m^3; $\nu = 1.51\cdot10^{-5}$ m^2/s;
- density of ejected air $\left.\rho_{\mathrm{I}}\right|_{t=0}=1.24$ kg/m^3 and air density $\rho_{\mathrm{III}}=\left(\left.\rho_{\mathrm{II}}\right|_{t=0}+\left.\rho_I\right|_{t=0}\right)/2=1.82$ kg/m^3 = const, the angle ϕ is equal to the local interaction angle of air ejected from the atmosphere, the pressure of which is taken $\left.P_{\mathrm{I}}\right|_{t=0}=0.1$ MPa, and ejecting air flow, $\phi = 14$ grad;

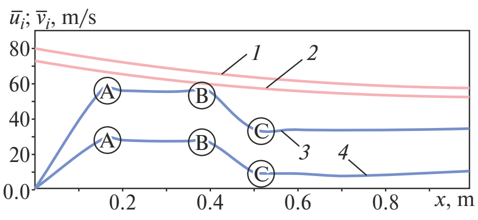

Fig. 2. Calculated movement velocities of the air ($\bar{u}_i$, i = I–III) and dispersed ($\bar{v}_i$, i = I–III) phases of the air mixture in the operating zone of the PTS with annular ejector

- dispersed phase of the air mixture is loaded using a vibrating loading body, where, according to the results of research [5], it is taken $\bar{v}_{x,\mathrm{I}} = 0.32$ m/s; $\bar{v}_{y,\mathrm{I}} = 0.25$ m/s and, accordingly, the average velocity of vibro-aerodynamic loading is $\bar{v}_{\mathrm{I}} = 0.4$ m/s.

Fig. 2 shows calculated regularities for two variants of compressed air leakage from the ejector: the initial velocity of air leakage from the nozzle device of the ejector is $\bar{u}_{\mathrm{II}}\big|_{t=0} =$ $= 80$ m/s (curve *1*) and $\bar{u}_{\mathrm{II}}\big|_{t=0} = 72$ m/s (curve *2*, which corresponds, for example, to a loss of compressed air leakage rate due to the leak in the air supply line of 10 %).

Analysis of regularities from Fig. 2 shows that the velocity of the air phase of air mixture relative to the length of the operating aria of the PTS annular ejector decreases according to a parabolic dependence, whose graph has the form of the *3rd* degree polynomial. With the approximation reliability value $R^2 \sim 1$, these regularities correspond to approximating functions

$$\bar{u}_i = 89.6x^3 - 98.24x^2 - 13.04x + 80\left(curve\ 1\right);$$

$$\bar{u}_i = 80.644x^3 - 88.419x^2 - 11.736x + 72\ \left(curve\ 2\right).$$

At the same time, the velocity of a dispersed phase particle of air mixture (curves *3* and *4*):

- rapidly increases at the maximum rate of leakage of ejecting flow from the nozzle device;

- slightly decreases at points *A*, when the velocity of ejecting air flow decreases, and the velocity of ejected air flow increases;

- stabilizes in the zones between points *A* and *B*;

- lightly increases at points B, where the velocity of the ejected air flow increases, and the velocity of the ejecting flow decreases;

- decreases in the zones between points *B* and *C*, where the maximum loss of kinetic energy of the ejecting air stream occurs due to its mixing with the ejected flow;

- stabilizes at the end of the mixing process of the ejected and ejecting air phases of the air mixture.

Thus, it can be stated that a 10 % decrease in the velocity of the air phase of the air mixture (curves *1* and *2*) leads to a decrease in the velocity of the solid phase of the air mixture (curves *3* and *4*) up to 50 % in zone where the ejecting flow acts to approximately 75 % at the end of the operating aria of the PTS annular ejector.

If for the dispersed phase of the air mixture in the initial conditions we consider another type of bulk material, then the calculations confirmed that the obtained patterns of the movement of the air mixture in the working area of the PTS annular ejector are preserved. At the same time, the granulometric composition and physicochemical properties of the transported material determine the choice of the transport pipeline diameter and the energy costs for pneumatic transportation. This necessitates an increase in the numerical value of the air phase velocity of the air mixture for heavier particles of the dispersed phase of the air mixture for their aerodynamic acceleration and movement in a suspended state.

To establish the regularities of the influence of the air mixture flow in operating aria of the annular ejector on the energy indicators of the PTS operation, we use the equation given in [4]. This equation describes the physical picture of air mixture flows interaction in operating aria of the PTS annular ejector, taking into account the vibro-aerodynamic method for loading the dispersed phase of the air mixture, and in our case, it has the form

$$\begin{gathered}\left(P_{\mathrm{II}}\big|_{t=0}\bar{u}_{\mathrm{II}}\big|_{t=0} + P_{\mathrm{III}}\bar{u}_{\mathrm{III}}\right)D^2 - \\ -\left(P_{\mathrm{II}}\big|_{t=0}\bar{u}_{\mathrm{II}}\big|_{t=0} - P_{\mathrm{I}}\big|_{t=0}\bar{u}_{\mathrm{I}}\big|_{t=0}\right)\left[D - 2\left(\delta + h\right)\right]^2 = \\ = \frac{2G_{\mathrm{II}}}{\pi}\left\{Q_1\left(\bar{u}_{\mathrm{III}}^2 - \bar{u}_{\mathrm{I}}^2\right) - \bar{u}_{\mathrm{II}}^2 + \bar{u}_{\mathrm{I}}^2 + \right. \\ \left. + 2Q_2 g\frac{\left[D - 2\left(\delta + h\right)\right]\left(k_2 - k_1\right)}{\mathrm{tg}\varphi}\right\},\end{gathered} \tag{9}$$

where $G_{\mathrm{II}} = \frac{\pi}{4}\bar{u}_{\mathrm{II}}\big|_{t=0}\rho_{\mathrm{II}}\big|_{t=0}\left\{D^2 - \left[D - 2(\delta + h)\right]^2\right\}$ is mass flow rate of compressed air supplied to the ejector, kg/s; Q_1 and Q_2 are specific flow rates of the air and dispersed phase of the air mixture per unit mass of compressed air supplied to the ejector; k_2 and k_1 are dimensionless weighting coefficients of particles of dispersed phase, respectively, at the end and at the beginning of the mixing zone of the air mixture in the ejector.

Using iteration method to solve (9), it can be concluded that for the initial conditions of the two-phase "gas–solid particles" flow in the PTS with the annular ejector at $k_2 = 1$ and $k_1 = 0.5$ and vibro-aerodynamic method of dispersed phase loading, a decrease in the velocity of the ejecting air flow, for example, by 10 % leads to a proportional increase in the specific flow rate of compressed air for moving the air (up to 13 %) and dispersed (up to 11 %) phases of the air mixture.

Conclusions. The regularity of the two-phase "gas–solids and particles" flow in the operating aria of the annular ejector has a parabolic dependence of distribution of the velocities of the air and dispersed phases of air mixture relative to the horizontal axis of the ejector operating aria. At the same time, the loss of kinetic energy of the compressed air (decrease in its leakage rate) supplied to the ejector leads to an almost directly proportional increase in the specific flow rate of compressed air for moving the air and dispersed phases of the air mixture.

Establishing the regularities of the two-phase "gas–solid particles" flow in the working zone of the PTS annular ejector is an urgent scientific and technical task aimed at investigating the processes of loading and acceleration of particles of the dispersed phase in this type of equipment.

Studying the influence of the compressed air outflow velocity from the nozzle device of the ejector on the kinematic parameters of air mixture flow at the beginning of the PTS transport pipeline makes it possible to evaluate the role of specific air consumption in the energy indicators of the use of this type of equipment. The results can be used in the design of new and improvement of existing PTS with an annular ejector to increase its efficiency in various technological processes at mining and metallurgical enterprises.

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Закономірності руху аеросуміші в робочій зоні кільцевого ежектора пневмотранспортної системи

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Мета. Встановити закономірності руху двофазного потоку «газ–тверді частинки» в робочій зоні кільцевого ежектора, де відбувається ежектування аеросуміші, виток стисненого повітря з соплового пристрою ежектора та змішування потоків аеросуміші у транспортному трубопроводі. Дослідити розподіл швидкостей дисперсної й повітряної фаз аеросуміші під час її завантаження й розгону у транспортному трубопроводі пневмотранспортної системи.

Методика. Дослідження базуються на фундаментальний підходах динаміки точки маси, аеродинаміки, теорії струминних течій та ітераційних методах числового рішення рівнянь.

Результати. Проаналізована механіка переміщення аеросуміші під дією ежекції та аеродинамічної сили в робочій зоні кільцевого ежектора й на початку транспортного трубопроводу. Виконана оцінка впливу закономірностей руху аеросуміші в робочій зоні кільцевого ежектора на енергетичні показники роботи пневмотранспортної системи.

Наукова новизна. Полягає в тому, що вперше отримані закономірності, які описують рух двофазного потоку «газ–тверді частинки» на завантажувальній ділянці пневмотранспортної системи з кільцевим ежектором. Це дозволило отримати характеристику розподілу швидкостей дисперсної й повітряної фаз аеросуміші під час їх завантаження та аеродинамічного розгону у транспортному трубопроводі. Також інноваційним підходом до ефективності застосування трубопровідного пневмотранспорту є оцінка енергетичних показників застосування пневмотранспортого устаткування ежекторного типу залежно від швидкості витоку стисненого повітря з ежектора.

Практична значимість. Реалізація результатів досліджень при модернізації існуючих і створенні нових пневмотранспортних систем з кільцевим ежектором дозволить підвищити ефективність їх використання в технологічних процесах переміщення дисперсних матеріалів на підприємствах гірничо-металургійного комплексу та в інших областях техніки.

Ключові слова: *пневмотранспортна система, аеросуміш, кільцевий ежектор, транспортний трубопровід*

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