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NUMERICAL SIMULATION OF TWO-PHASE FLOW IN JET MILL EJECTOR WITH ADDITIONAL ENERGY SUPPLY

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Нові підходи до підготовки та обробки сировини в процесі струминного подрібнення набувають все більшої ваги. Це пов'язано з необхідністю підвищення ефективності подрібнення та зниження витрат енергії, підвищення надійності і тривалості служби обладнання та розширення можливості використання струминного млина в різних галузях. Все це обумовлює важливість розробки та впровадження нових підходів до організації двофазного потоку в каналах струминного млина. Ціль роботи – дослідити спосіб удосконалення організації двофазного потоку в трактах газоструминного млина. Чисельні дослідження двофазної течії в ежекторі струминного млина показали перспективність використання додаткового підведення енергоносія через стінки розгінної трубки ежектора для підвищення ефективності його роботи. Керування газовими потоками в ежекторі млина за рахунок використання енергії додаткових потоків газу дозволяє підвищити швидкість основного потоку на виході з розгінної трубки ежектора та створює захисний шар навколо стінок трубки для запобігання зносу конструкції. А встановлення конічного насадка на кінці розгінної трубки забезпечує безвідривну течію без утворення вихрових зон та рівномірний розподіл швидкостей на виході з ежектора. Розроблено нові рішення та рекомендації щодо підвищення ефективності організації двофазного потоку в каналах газоструминного млина. Наукове значення результатів полягає у розробці газодинамічного способу керування газовими потоками в трактах струминного млина, який забезпечує можливість рівномірного прискорення часток сипучого матеріалу та зменшення зносу конструктивних елементів млина. Практичне значення полягає у розробці рекомендацій щодо підвищення ефективності організації двофазного потоку в трактах газоструминного млина. Область застосування результатів – горно-металургійна, будівельна, хімічна, харчова промисловість і сільське господарство. Результати досліджень будуть використані для подальшої розробки наукових основ вдосконалення газоструминних подрібнювачів.

Ключові слова: *ежектор струминного млина, керування двофазними потоками, чисельне моделювання, підвищення ефективності струминного подрібнення.*

New approaches to the preparation and processing of raw materials in the process of jet grinding are gaining more and more importance. This is due to the need to increase the efficiency of grinding and reduce the energy consumption of the equipment, increase its reliability and service life, and expand the possibility of using the jet mill in various industries. All this determines the importance of developing and implementing new approaches to two-phase flow organization in the channels of a jet mill. The goal of this work is to investigate a method for improving two-phase flow organization in the gas jet mill tracts. Numerical studies of a two-phase flow in the ejector of a jet mill showed the advisability of using an additional energy supply through the walls of the accelerating tube of the ejector to increase the efficiency of its operation. Controlling the gas flows in the mill ejector by using the energy of additional gas flows allows one to speed up the main flow at the exit of the ejector accelerating tube and form a protective layer around the tube walls to prevent their wear. The installation of a conical nozzle at the end of the accelerating tube prevents flow separation and vortex formation and provides a uniform velocity distribution at the ejector exit. The paper presents new solutions and recommendations on improving the efficiency of two-phase flow organization in the ducts of a gas jet mill. The scientific significance of the results lies in the development of a gas-dynamic method for controlling the gas flows in the jet mill tracts, which provides a uniform acceleration of the bulk material particles and reduces mill wear. The practical significance lies in the development of recommendations on increasing the efficiency of two-phase flow organization in the gas jet mill tracts. The results may be used in mining, metal manufacture, construction, the chemical and the food industry, and agriculture, and they will be employed in further development of scientific fundamentals of gas jet mill improvement. .

Keywords: *jet mill ejector, control of two-phase flows, numerical studies, improvement of efficiency of jet grinding.*

Introduction. Grinding of materials is an important element of modern technological processes. In countercurrent jet mills, the product is crushed by the collision of the opposing streams particles. This makes it possible to transfer very high energy to the particles. Thus, with particle velocities at the exit from the accelerating tube of the order of 150 m/s – 200 m/s, the impact speed can reach 300 m/s – 400 m/s, which allows grinding products of a wide range of hardness regardless of the particle collision nature [1, 2].

At the same time, classic ejectors of countercurrent jet mills have a number of disadvantages that significantly reduce their use.

First, it is wear and tear of the elements of the accelerating tube construction. This leads to contamination of the finished product, as well as to changes in the gas-dynamic parameters of the mill. For example, the flow rate at the outlet can decrease due to an increase in the diameter of the accelerating tube, which in practice can reach 10 % of the original [3].

Second, low performance due to a relatively small density of particles in the accelerating tube. This is due to the fact that there is a limitation of the flow of the initial product due to the so-called closing of the mill, i.e., a regime when the energy of the active gas is insufficient to accelerate the two-phase flow [4, 5]. At the same time, the probability of collision of particles in oncoming flows is small. It is necessary to repeatedly return the material from the classifier to the additional grinding, which significantly reduces the energy efficiency of the mill.

The main purpose of the ejector of the jet mill is to accelerate the two-phase flow at the exit from the accelerating tube. The nature of the velocity distribution in the outlet section and the density of particles in the flow are also important. In traditional ejectors of jet mills, the condition of uniform distribution of velocity and particle density at the outlet is not fulfilled [1, 6, 7].

One of the possible ways to improve the characteristics of the jet mill ejector is to create a wall layer of pure gas in the region of the accelerating tube wall by additional energy supply to the accelerating tube.

The purpose of this work is to investigate this method of two-phase flow organization in the gas jet mill tracts.

Formulation of the problem. The task is solved by the fact that on the periphery of the accelerating tube of the ejector of the gas jet mill, a channel for the additional energy supply is installed, which enters the accelerating tube through slit holes, and at the end of the cylindrical accelerating tube, a conical nozzle is installed with a taper angle of 1.5° – 3° and a length of 0.15 to 0.25 of the accelerating tube length. The slit holes are located at an angle of 20°– 30° to the longitudinal axis of the ejector, which provides the best conditions for protecting the walls of the accelerating tube from the influence of the two-phase flow. The conical nozzle allows you to organize the flow inside the accelerating tube so that you get a more uniform flow at the exit.

Fig. 1 shows the scheme of the proposed device, which includes: bulk material supply hopper 1, through which the material for additional grinding ("re-grinding") from the classifier is supplied through pipeline 2, and raw material is supplied through pipeline 3; central nozzle 4; active air supply nozzle 6; accelerating tube 7 with a conical nozzle 5; channel 8 of an additional energy supply.

Fig. 2 shows the flow diagram of the main, passive and additional flows in the ejector accelerating tube.

Accepted notation: 1 – supply of a mixture of air and solid particles; 2 – the nozzle of the axial feed of the energy carrier; 3 – supply of the main flow of the energy carrier; 4 – accelerating tube; 5 – conical nozzle; 6 – additional energy supply, which enters through the slit holes 7 to the ring nozzle 8 at an angle of 20° – 30° to the longitudinal axis of the ejector.

After starting the jet mill, the flow of the carrier working fluid picks up the flow of primary bulk material from the loading hopper and enters the accelerating tube, the wall of which has slit holes through which gas is supplied from the channel of the additional energy supply, evenly distributed along the cross section of the ring. After mixing the flows in the accelerating tube, the gas-dispersed flow enters the grinding chamber for grinding.

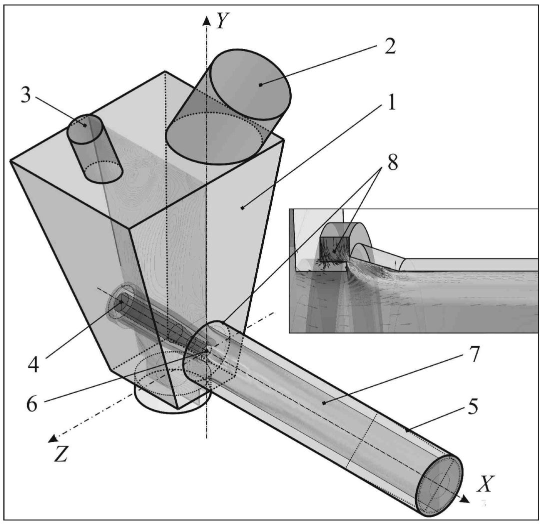


Fig. 1

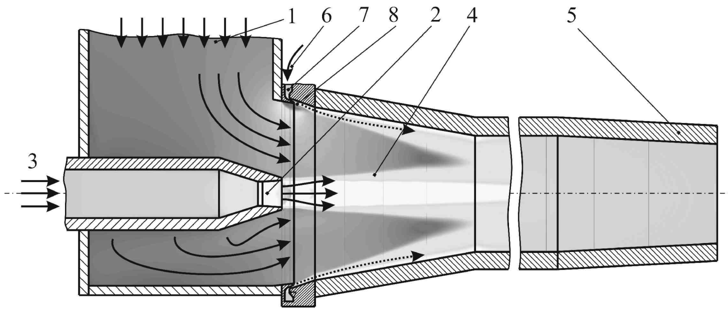


Fig. 2

The output data for numerical simulation are as follows:
1) for gas flow (air):
– temperature T = 300 K;
– heat capacity C_p = 1006.43 J/(kg·K);
– density ρ = 1.225 kg/m^3;
– thermal conductivity 0.0242 W/(m·K);
– viscosity according to the Sutherland formula:

$$\mu = \mu_0 \left(\frac{T}{T_0} \right)^3 \frac{T_0 + C}{T + C},$$

where μ is the dynamic viscosity, kg/(m·s); μ_0 – control viscosity at a certain temperature T_0, kg/(m·s); T is the set temperature, K; T_0 – control temperature, K; C is Sutherland's constant; $\mu_0 = 1.716\cdot10^{-5}$ kg/(m·s); T_0 = 273.11 K; C = 110.56; – molecular weight 29.966 kg/kmol; 2) for a discrete phase: – material – dolomite; –

density ρ_d = 2872 kg/m^3; – heat capacity C_p = 910 J/(kg·K); – particle diameter D_d = 0.5 mm; – mass flow rate $\dot{m}_d$ = 0.2 kg/s.

To study the flow in the ejector, the following boundary conditions have been set:

1) active flow:

– inlet pressure p_{0act}= 0.6 MPa;

– gas temperature t_{0act}= 20 ºC;

– hydraulic diameter D_{gDact} = 28.0 mm;

– intensity of turbulence 5 %;

2) passive stream:

– inlet pressure p_{0pass} = 0.1 MPa;

– gas temperature t_{0act} = 20 ºC;

– hydraulic diameter $D_{gD\ pass1}$= 120.0 mm, $D_{gD\ pass2}$= 50.0 mm;

– intensity of turbulence 5 %;

3) additional flow:

– inlet pressure p_{0inj} = 0.6 MPa;

– gas temperature t_{0inj} = 20 ºC;

– hydraulic diameter D_{gDing}= 11.35 mm;

– intensity of turbulence 5 %;

4) output flow (mixture):

– inlet pressure p_{0out} = 0.1 MPa;

– gas temperature t_{0out} = 20 ºC;

– hydraulic diameter D_{gDout}= 90.0 mm;

– intensity of turbulence 5 %.

– return from the classifier through pipeline 2 (see Fig. 1) to the "pre-mill" (outlet-passiv-B), inlet pressure p_{0pass} = 0.1 MPa;

– introduction of additional material through pipeline 3 (see Fig. 1) (outlet-passiv-S) at a non-zero velocity of the gas phase (w_{0pass} = 0.5 m/s).

Discrete phase speeds:

– outlet-passiv-B w_{dB} = –25.0 m/s;

– wall-passiv-S w_{dS}= –0.5 m/s.

Mathematical model. The flow calculation in the jet mill ejector has been based on the SST k-ω turbulence model. The motion of the solid phase in ANSYS Fluent is modeled by numerically solving the unsteady Reynolds Averaged Navier–Stokes (URANS) equations. In the Navier–Stokes equations, the components of velocity, temperature and related variables are averaged according to Favre (marked with a tilde from above in the formulas), density and pressure are averaged according to Reynolds (dashed from above).

The URANS equations have the form [8]:

– the continuity equation:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial\bar{\rho}\tilde{u}_j}{\partial x_j}=0,$$

where ρ is the density, kg/m^3; u_j is the value of the instantaneous speed, which consists of the averaged and pulsating components, m/s; t is the time, s; x_j is the coordinate, m; j = 1, 2, 3;

– the momentum equation:

$$\frac{\partial\left(\bar{\rho}\tilde{u}_i\right)}{\partial t}+\frac{\partial\left(\bar{\rho}\tilde{u}_i\tilde{u}_j\right)}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial\left(\bar{\tau}_{ij}^{lam}+\bar{\tau}_{ij}^{turb}\right)}{\partial x_j},$$

де i = 1, 2, 3; $P = \bar{\rho}R\tilde{T}$ is the pressure, MPa; R is the gas constant, J/(kg·K), T is the temperature, K; $\bar{\tau}_{ij}$ is the averaged tensor of viscous stresses;

– the energy equation:

$$\frac{\partial\left(\bar{\rho}E\right)}{\partial t}+\frac{\partial\left(\left(\bar{\rho}E+P\right)\tilde{u}_j\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left(-q_j^{lam}-q_j^{turb}+\tilde{u}_i\left(\tau_{ij}^{lam}+\tau_{ij}^{turb}\right)\right),$$

where q is the heat flow due to thermal conductivity; E is the total energy, which is equal to the sum of the averaged internal energy and kinetic energy of turbulent pulsations, J.

For the laminar flow:

$$\bar{\tau}_{ji}^{\;lam}=\mu\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial\tilde{u}_k}{\partial x_k}\right),$$

where μ is the dynamic viscosity coefficient, N·s/m^2; k = 1, 2, 3; δ_{ij} is the Kronecker symbol;

$$q_j^{\;lam}=-\lambda\frac{\partial\tilde{T}}{\partial x_j},$$

where λ is the gas thermal conductivity coefficient, W/(m·K).

For the turbulent flow:

$$\bar{\tau}_{ji}^{\;turb}=\mu_t\left(\frac{\partial\tilde{u}_i}{\partial x_j}+\frac{\partial\tilde{u}_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial\tilde{u}_k}{\partial x_k}\right)-\frac{2}{3}\delta_{ij}\bar{\rho}k,$$

and the component $\frac{2}{3}\delta_{ij}\bar{\rho}k$ makes a small contribution, so it can be neglected; μ_t is the turbulent component of the dynamic viscosity, N·s/m^2;

$$q_j^{\;turb}=\lambda_t\frac{\partial\tilde{T}}{\partial x_j},$$

where λ_t is the turbulent component of the thermal conductivity coefficient, W/(m·K).

Sutherland's formula [9] is used to calculate the dynamic viscosity coefficient:

$$\mu=\mu_0\left(\frac{T}{T_0}\right)^{3/2}\frac{T_0+C}{T+C},$$

where μ_0 is the viscosity coefficient at $T = T_0$, for T_0 = 273 K the coefficient μ_0 = $1.71\cdot10^{-5}$ Н·с/м^2; C is the constant, for gas C = 117.

To close the averaged Navier–Stokes equations, the equations of the transfer of kinetic energy of turbulence and the equation of the relative dissipation rate are introduced [10]:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho k u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k ,$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho\omega u_i)}{\partial x_i}=\frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right)+G_\omega-Y_\omega+D_\omega+S_\omega ,$$

where k is the turbulent kinetic energy, J; ω is the specific dissipation rate, m/s; Γ_k, Γ_ω are the effective diffusion k and ω, respectively; G_k , G_ω are the generative terms; Y_k , Y_ω are the dissipative terms; D_ω is the cross term; S_k , S_ω are the custom output conditions.

Air with a temperature of 300 K has been used as the working medium. Research has been carried out taking into account the following assumptions:

– mixed gases obey the equation of an ideal gas state and have the same composition;

– the profile of pressure, temperature and velocity in the initial section is uniform;

– heat transfer on the walls can be neglected.

The Lagrangian approach has been used to model the motion of discrete particles in the continuous phase in ANSYS Fluent. Particles of the discrete phase have been assumed to be spheres. The forces acting on the particle are due to the difference between the velocity of the particle and the flow velocity of the solid phase, as well as the displacement of the medium of the solid phase by this particle. The equation of motion of such a particle has the form [1]

$$m_p\frac{du_p}{dt}=3\pi\mu d_p C_{cor}\left(u-u_p\right)+\frac{\pi d_p^3\rho}{6}\frac{du}{dt}+\frac{\pi d_p^3\rho}{12}\left(\frac{du}{dt}-\frac{du_p}{dt}\right)+$$

$$+F_e-\frac{\pi d_p^3}{6}\left(\rho_p-\rho\right)\bar{\omega}\times\left(\bar{\omega}\times\bar{r}\right)-\frac{\pi d^3\rho_p}{6}\left(\bar{\omega}\times u_p\right),$$

where m_p is the particle mass, kg; u_p is the particle velocity, m/s; d_p is the particle diameter, mm; C_{cor} is the viscous resistance coefficient, Pa·s; F_e is an external force that directly acts on a particle (for example, the force of gravity or the force of an electric field), N; $\bar{\omega}$ is the rotation angular velocity, rad/s; $\bar{r}$ is the radius vector (in the case of considering motion in the relative frame of reference).

Algorithms implemented in ANSYS Fluent make it possible to model the influence of a discrete phase on the continuous phase flow. In the first approximation, the density and viscosity of the solid phase substance and some other values are multiplied by $(1 - \alpha_p)$, where α_p is the specific volume occupied by the particles. Then, at each time step, changes in the mass, momentum, and energy of the particles are calculated, and these changes are added, respectively, to the equations of conservation of mass, momentum, and energy for the continuous phase flow. Therefore, the calculation of the flow of the solid phase and the calculation of the movement of particles are performed together.

Results and their discussion. We have performed a two-phase flow analysis for two ejector constructions:

1) a traditional ejector with an axial supply of the energy carrier and a lateral supply of the material of the jet mill of the Vilnohorsk Mining and Metallurgical Combine (VMMC);

2) our proposed ejector with additional energy supply along the periphery of the accelerating tube and a conical nozzle (Fig. 3), which has been developed on the basis of the VMMC mill ejector.

In fig. 3, the following designations are adopted: 1 is an additional energy supply; 2 is an additional flow formation zone; 3 is the minimum cross-section; 4 is the flow of additional energy supply; 5 is the main stream.

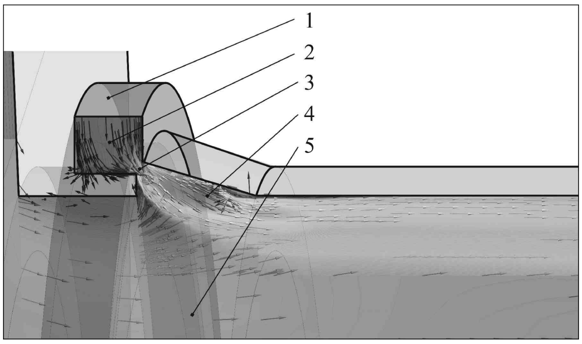
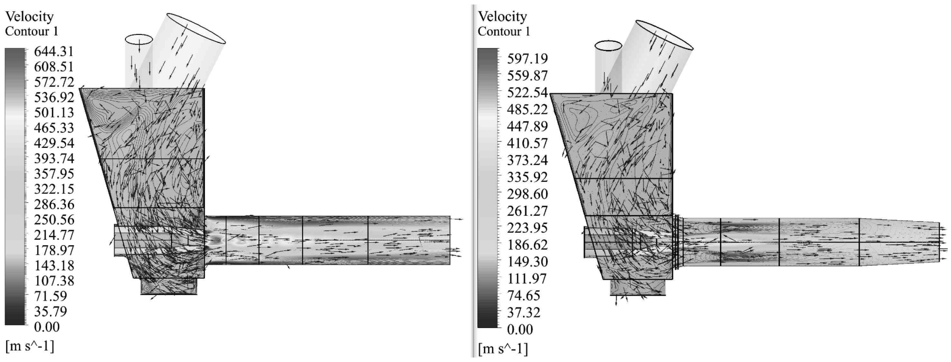


Fig. 3

The character of the flow in the ejector unit of the VMHK jet mill has a complex spatial character (Fig. 4). Fig. 4, a) illustrates the velocity vectors in the existing ejector of the VMHK mill, and Fig. 4, b) illustrates the velocity vectors in the version of the ejector proposed by us with an the additional energy supply and a conical nozzle at the end of the accelerating tube.

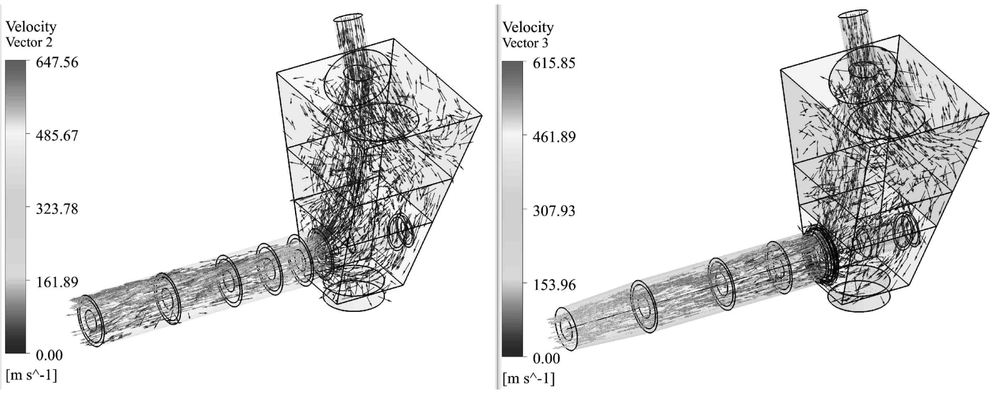
The vortex structure of the flow, due to the asymmetric introduction of the passive flow, formed in the inlet part, spreads along the accelerating tube. Moreover, it has long vortices up to the formation of local zones of turning current.

In our proposed ejector model, despite significant vortices in the feeding hopper, the flow is leveled in the acceleration zone. Only minor vortices are observed in the initial section of energy transfer from active to passive flows. Fig. 5 illustrates the differences between the flow structure in the ejector of the VMHK mill a) and in the ejector with additional energy supply b).



a) b)

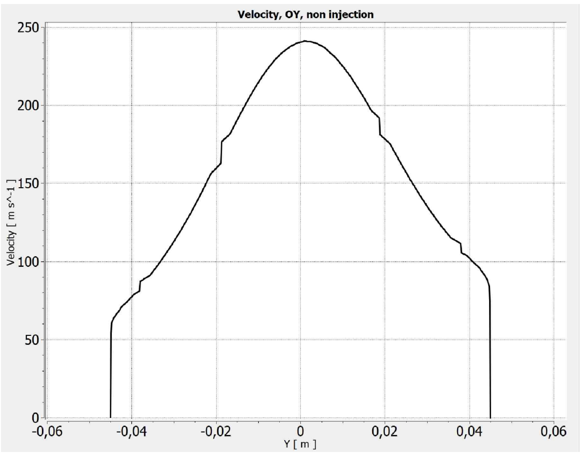
Fig. 4



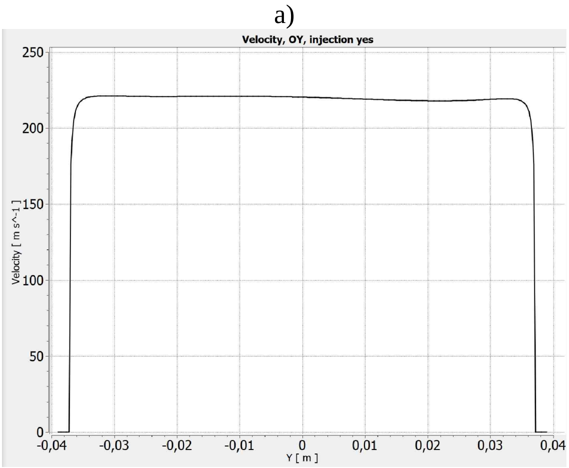
a) b)

Fig. 5

The relatively short length of the accelerating tube of the VMHK mill ejector (450 mm with a diameter of 90 mm, which corresponds to the industrial prototype) does not allow to ensure a uniform flow velocity at the exit, which can be seen in fig. 6, a). Instead, the conical nozzle at the end of the tube and the additional energy supply contribute to the equalization of the flow (Fig. 6, b)).



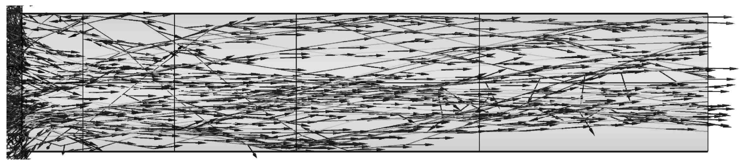
a)



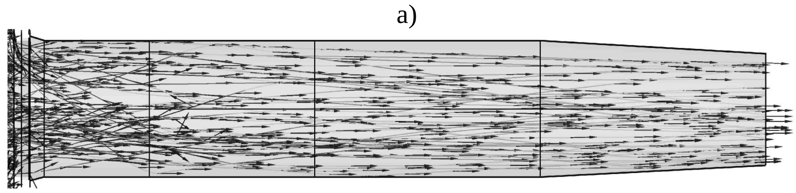
b)

Fig. 6

The trajectories of solid particles generally correspond to the nature of the gas phase flow, while inertial forces have a significant effect, especially in areas of significant velocity gradients (Fig. 7). Fig. 7, a) shows the trajectories of the solid particles of the VMHK mill ejector; fig. 7, b) shows the trajectories of the solid particles of our proposed ejector.



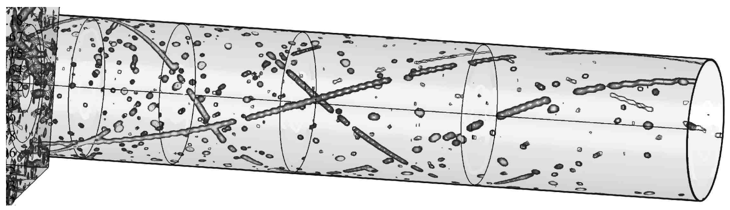
a)



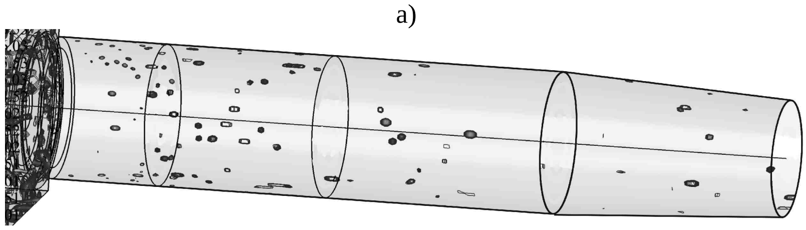
b)

Fig. 7

The erosive effect on the structural elements of the flow part of the node is determined by the speed and density of particles on the wall. Fig. 8 shows a comparison of the density of solid particles on the wall of the accelerating tube of the VMHK mill ejector, a) and the proposed ejector, b).



a)



b)

Fig. 8

The additional energy supply will allow to actively influence the two-phase flow to form the optimal parameters of the latter at the exit from the ejector unit, depending on the size and physical and chemical properties of the source material (see Fig. 6).

In addition, the conical nozzle significantly stabilizes the flow and provides a stable wall layer formed by feeding the energy carrier through the annular additional nozzle.

The conical nozzle allows for a more even distribution of the average velocity in the output section of the ejector compared to the significant asymmetry of the flow for a cylindrical tube.

The nature of the flow in the ejector with additional energy supply due to the conical nozzle has the following advantages:

– there are no vortex zones along the entire length of the accelerating tube, as well as zones of positive pressure gradient;

– the uniformity of the velocity field in the exit section of the ejector increases significantly;

– a stable, uniform wall layer is provided from the annular additional nozzle.

Therefore, the use of the additional energy supply through the annular nozzle into the ejector of the jet mill allows you to obtain a uniform wall layer that protects the walls of the accelerating tube from wear. And the conical nozzle for the tube ensures a continuous flow without the formation of vortex zones and a uniform distribution of velocities at the exit from the ejector.

Conclusion. Numerical studies in a gas jet mill confirmed the perspective of using the optimal organization of material flow at the entrance to the grinding chamber to increase the efficiency of gas jet grinding. Based on the modernization of the ejector construction of the jet mill, a method of increasing its efficiency has been developed.

The scientific significance of the results lies in the development of a gas-dynamic method of controlling gas flows in the gas jet mill tracts.

The practical significance of the obtained results lies in the determination of the construction parameters of the ejector, which ensure a uniformly accelerated flow at the exit from the ejector and a stable wall layer to protect the walls of the structure from wear.

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