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IMPROVING INDUSTRIAL PIPELINE TRANSPORT USING RESEARCH OF REGULARITIES OF FLOW OF MIXTURES IN MATERIAL PIPELINE

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Виконано дослідження явищ, що відбуваються в транспортному трубопроводі при переміщенні сумішей в нестаціонарних режимах масопереносу. Запропонована реологічна модель руху неньютонівських рідин. Показано, що стохастичні режими руху сумішей виникають при переході через перемежуваємість, тобто є наслідком зіткнення асимптотично стійких і нестійких станів руху

Ключові слова: трубопровідний транспорт, сипучий матеріал, перемежуваємість, режими руху, водовугільне паливо, енергозбереження

Выполнено исследование явлений, происходящих в транспортном трубопроводе при перемещении смесей в нестационарных режимах массопереноса. Предложена реологическая модель движения неньютоновских жидкостей. Показано, что стохастические режимы движения смесей возникают при переходе через перемеживаемость, то есть являются следствием столкновения асимптотически устойчивых и неустойчивых состояний движения

Ключевые слова: трубопроводный транспорт, сыпучий материал, перемеживаемость, режимы движения, водоугольное топливо, энергосбережение

1. Introduction

Currently, industrial enterprises of Ukraine widely use high-pressure pneumatic conveying systems with a number of disadvantages:

– high velocity of mixtures flow in the pipeline, hence high energy consumption for transporting air-fuel mixtures;

– high wear of pipelines and ancillary equipment;

– degradation of particles of bulk materials;

– pipeline blockage;

– need to purify large volumes of air emitted into the environment;

– unstable sedimentation of material particles in the pipeline while using hydraulic transport.

In Ukraine, there is an acute problem of oil and gas shortage. An alternative to these energy sources is coal water fuel (CWF), obtained from finely ground coal of any brand, water and reagent-plasticizer. Use of CWF in industry has a number of advantages:

– CWF is relatively environmentally friendly source of energy, its combustion products contain much less soot, nitrogen and sulphur oxides;

– CWF is an economical type of fuel;

– it has sufficiently high calorific value and can reduce costs on its transportation through usage of pipeline transport. At the same time, hydrotransport systems design for CWF has some specific features that are not addressed sufficiently.

A significant number of industrial enterprises in Ukraine operate high-pressure pneumatic conveying systems, which are widely used and have the above-mentioned disadvantages. These pneumatic conveying systems are the key object in the complex chain of transportation organization of bulk materials at the enterprise. Any negative factors and failures in the system operation lead to forced stoppage in production, disruption of operating technologies and increased energy consumption for their operation and maintenance.

The most important task of hydrotransport systems is transportation of alternative fuels, a promising one of which is CWF. In this case, the rational choice of concentration and granulometry of the solid component of CWF, as well as the choice of an adequate transportation mode, determines the efficiency of the entire hydrotransport system. The greatest need for improvement of such systems is evident against the background of acute shortage of imported energy resources in Ukraine.

In view of this, development of physical and scientific foundations for creation of new, highly efficient energy-saving methods of pipeline transport is an urgent task of modern science.

2. Literature review and problem statement

Work [1] presents differential equations for dynamics of both homogeneous and heterogeneous media that have

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become the basis for further research and development in the field of pipeline transport.

Works [2, 3] consider the laws of flow of bulk materials using pneumatic and hydraulic methods of transportation. The basis of this theory is separation of transported materials into classes. Then equations of flow of mixtures are considered and the main parameters of hydraulic and pneumatic conveying systems are determined for each class according to grain composition of mixtures.

Works [1, 4] describe the main aspects of mechanics of multiphase media with different structures (gas mixtures, bubbly liquids, gas and heat carriers of vapour-liquid boilers), discuss methods for describing interfacial interaction in dispersive media. Works [1, 2] give the theory of sound, shock and kinematic waves and oscillatory motions in two-phase media. On the basis of methods and approaches outlined in sources [5, 6], there is considered mechanics of oscillation and vibro-pneumatic conveying of bulk materials with regard to flow mode of individual particles aloft in suspension. The averaged energy balance equation of the *i*-phase is proved and provided, taking into account the effect of surface, bulk, interfacial and internal forces of the given volume [6]. However, practical use of these approaches is unlikely feasible due to the need of using a lot of hardly determinable parameters.

Works [7, 8] consider the issues of fluidization of homogeneous media, as well as applied mechanics of heterogeneous media. Researches [9–11] describe the results of studies of various parameters of pneumatic conveying systems during turbulent flow, transportation of gas-material flow, velocity and pressure losses.

There are carried out studies that focus on the effect of silting of dams, which is caused by instability and sedimentation volatility of hydraulic fluids. Experiments in work [12] with finely dispersed coal water suspensions showed that the nature of their flow is somewhat different from the flow of ideal viscoplastic fluid. Actual flow starts at lower shear stresses, it follows from the theory of viscoplastic flow. There was also found the phenomenon of spontaneous flow cessation at low velocity.

This issue is given a lot of attention in papers [13, 14]. They present research of processes of hydraulic transportation of highly concentrated suspensions at different shear stresses, transportation velocity and concentrations of the solid ingredient. In addition, much research is devoted to issues of sedimentation stability of suspensions, depending on various factors. It follows from the obtained data that the rational choice of concentration and particle size of the solid ingredient, and the choice of an adequate transportation mode determine effectiveness of the entire hydrotransport system [15, 16].

3. The aim and objectives of the study

The aim of this work is to study the regularities of flow of mixtures in material pipeline and their features referring to hydraulic and pneumatic transport. On this basis, it becomes possible to develop physical and scientific bases of creation of new, highly efficient energy-saving methods of pipeline transport.

To achieve this aim, the following tasks have been identified:

– to perform analysis of the processes taking place in the pneumatic transport and hydraulic transport pipelines during transportation of bulk materials and coal water fuel respectively;

– to study the process of self-organization of mass transfer and phenomena occurring in the transport pipeline during flow of mixtures in non-stationary mass transfer modes;

– to propose a rheological model for flow of non-Newtonian fluids;

– to establish the main tasks of new technical solutions aimed at improving the pipeline transport.

4. Materials and methods for studying regularities of flow of mixtures in the material pipeline

The modern approach to development of promising pipeline transportation methods [17–20] is based on the research of phase states and transitions of air-fuel and hydraulic mixtures, conditions of their formation and preservation of stability in different parts of the transport pipeline. Mixtures flow is accompanied by complex processes, which are consequences of a variety of combinations of phases and their structures, interfacial and intraphase interactions and transitions.

Pneumatic and hydraulic transport transit solid material using the carrying flow (either gas or liquid) in the course of its operation, then with a certain degree of probability it can be argued that they comply with the fundamental laws of physics.

Studies of flow modes of homogeneous and heterogeneous media (gas-solids) in pneumatic transport pipeline [17–20] have shown that transition from laminar to stable turbulent flow through a number of unstable intermediate states takes place in the pipeline. Within one pipeline there may be two or more flow modes with their mutual sequence of transitions. In pneumatic systems operating in wave and batch modes of flow of air-fuel mixtures, in addition to general incremental flow of bulk material along the transport pipeline, there take place inside wave and inside batch turbulence characterized by formation of a large number of vortices. At the same time characteristics of turbulent flow mode are kept, i. e., its disequilibrium, a large number of macroscopic degrees of freedom, significant and often decisive role of hydrodynamic fluctuations arising due to excitation of a large number of macroscopic degrees of freedom, its unpredictability to a great extent.

Transportation of bulk materials using transport pipeline under the influence of the carrying flow can be seen as an open system, which possesses unevenness associated with energy supply and resistance to flow, a large number of interacting subsystems of dynamic variables, viscosity and medium shear stress (its intrinsic properties), macroscopic interaction among particles and carrying flow. The peculiarity of this system is the phenomenon of intermittency, i.e. sequential change in regular and temporary time states of motion (the processes of formation and destruction of structures, transitions of laminar flow into the turbulent one and vice versa). Under certain conditions in pneumatic conveying pipeline there emerge ordered structures and forms of motion of the originally disordered, irregular forms without special ordering external influences on the system [21–23].

Adoption of the basic postulates of synergy [21–24]: relative degree of state order in open systems, helping to distinguish the “order” from the “chaos”; criterion of the degree of chaos or order *K* – entropy (entropy of Krylov-Kolmogorov-

Sinay), Lyapunov exponents, Boltzmann-Gibbs-Shannon entropy (H – Boltzmann's theorem of thermal equilibrium, S-theorem); adoption of entropy differences as Lyapunov function, and adoption of the fact that the laminar flow accepted as a state of chaos is unstable; entropy production principle – the system is moving towards reducing entropy production; turbulent flow is more ordered than laminar flow; by the criterion of S-theorem transition from laminar flow to the turbulent one is a process of self-organization; establishing new macroscopic relations among individual areas and significant complication of the structure suggest that constantly occurring nonequilibrium phase transitions in pneumatic conveying pipeline are carried out according to $O \leftrightarrow C$ (order $\leftrightarrow$ chaos), i. e. under the scheme of self-organization.

State of local equilibrium in laminar flow is characterized by the following distribution [22]:

$$f_l(r,v)=\left(\frac{m}{2\pi kT}\right)^{3/2}\exp\left[-\frac{m\left(vV_l(r)\right)^2}{2kT}\right], \tag{1}$$

where V_l is an average velocity of laminar flow.

The derivative of the control parameter (the Reynolds number is accepted as a control parameter) is:

$$\frac{d}{d\,\mathrm{Re}}(S_l-S_T)>0, \tag{2}$$

where S_l is local entropy of laminar flow; S_l is averaged entropy of turbulent flow, allowing to consider transition from laminar flow to the turbulent one as a steady process of self-organization of flow modes of air-fuel mixtures in pneumatic conveying pipeline.

5. Results of the research of methodological approaches to improving pipeline transport based on the synergetic concept

Mixtures flow in a pipeline is accompanied by dissipation of energy for transportation and motion in large-scale vortex formations within a single volume. In case of establishing asymptotically stable state of flow in the mainline pipeline, balance of external forces is equivalent to forces of the resistance to motion:

$$\sum F_{ext}=\sum F_{res}. \tag{3}$$

Dependence of energy of E mixture amount at steady motion on the ratio of external forces and forces of resistance to motion (ε_E) and external energy force (ε_{EX}). shows that at values close to $\varepsilon_E \cong \varepsilon_{EX}$, the system is in an unstable state.

In case of pneumatic transport, structures are easily ruined, passing in a stable state: transportation in flight mode of individual particles in suspension or fluidized flow. Individual particles of flowing mixture volume have the properties required for transition into the intermitting mode. Presence of internal friction in the given system implies existence of an attractor, i. e., asymptotic limit $(t \to \infty)$ of decisions, which is not directly affected by the initial condition – the starting point. Oscillation motion of particles exists in limited, poorly overlapped intervals of the investigated parameter $(\tilde{P})$ values. Stochastic mode should be established at such a value of parameter $(\tilde{P})$, when it goes beyond $\left|[\tilde{P}_1,\tilde{P}_2]_2\right.$ towards higher or lower values, for example:

$$\tilde{P}(t)=\frac{\tilde{P}_1+\tilde{P}_2}{2}+(\tilde{P}_1-\tilde{P}_2)\sin\varepsilon t, \tag{4}$$

where ε is a small parameter; t is time interval.

In this case, stochastic motion modes, both in pneumatic and hydraulic transport, arise while passing through intermittence, i.e. they are the result of collision of asymptotically stable and unstable motion states $\left(\tilde{P}=\tilde{P}_1, \tilde{P}=\tilde{P}_2\right)$. Another reason of transition is explained in the following way: there is always arbitrarily small perturbation of motion (Landau scenario) when an attractor with a large number of independent frequencies becomes a so-called "strange attractor", containing stochastic attracting trajectories:

$$-P=\beta\bar{\Theta}^2 \text{ or } \bar{\Theta}^2=\frac{-P}{\beta}, \tag{5}$$

where β is a numerical coefficient; $\bar{\Theta}$ is motion velocity of particles.

Fig. 1 is a graph of dependence of energy of air-fuel mixture volume $\bar{E}$ with steady state of motion on value $\tilde{P}$, where $\tilde{P}=\frac{P}{\beta}$. Pecked lines show corresponding unstable states of motion. The graph can be divided into three areas. Thus:

– when $\tilde{P}<\tilde{P}_1$ (area I), oscillatory motion of material particles takes place, without separation from the surface of the pipe;

– when $\tilde{P}>\tilde{P}_2$ (area III) – particles are in flight (transportation mode is in suspension);

– when $\tilde{P}_1<\tilde{P}<\tilde{P}_2$ (area II) – particles are in an unstable state. In the latter case, particles execute conditionally periodic translational and rotational motions. The structure has a small margin of stability and is easily ruined, passing to state $\tilde{P}<\tilde{P}_1$ or $\tilde{P}>\tilde{P}_2$.

Area II analysis shows that individual particles of the volume of the flowing mixture have properties to transfer to the intermitting mode at slow change in parameter $\tilde{P}$. Stochastic mode should be established at such a change of $\tilde{P}$, when this parameter goes beyond interval $\left[\tilde{P}_1,\tilde{P}_2\right]$, both to higher and lower values. This approach makes it possible to explain stochastization of motion of rather complicated such non-conservative dynamical systems with lots of variables as pneumatic conveying systems for transporting bulk materials.

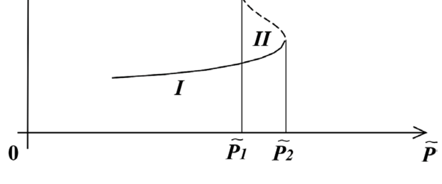

Fig. 1. Dependence of air-fuel mixture energy on the ratio of external forces and resistance forces: $\tilde{P}, \tilde{P}_1, \tilde{P}_2$ are the investigated parameters of the oscillatory motion of particles; $\bar{E}$ is the energy of the air-fuel mixture volume of the steady motion state; I, II, III are states of the material particles

Similar dependence of hydraulic fluid energy on the ratio of external forces and resistance forces can be created in case of hydraulic transportation.

Flow of mixtures with inner waves and inner portions turbulent motions is considered as a process of self-organization with collective motions, determining the efficiency coefficients of transfer of momentum, force and mass of the moving material flow. The process of self-organization of mass transfer in pneumatic conveying transport is carried out by additional energy supply of the moving material flow. Energy supply is realized by carrying gas, oscillation or combined actions of several factors. Shape and roughness of particles and walls of the pipeline, carrying flow turbulence, system entropy, oscillatory processes observed during flow of bulk materials in the transport pipeline also contribute to creation of additional vorticity of the flow.

Hydraulic fluids and coal water suspensions consist of two separate phases: water – continuous medium (continuum) and solid particles (discrete medium). Taken separately, each of these phases is characterized by its specific properties. The discrete solid phase is characterized by its mechanical parameters, grain size composition, angles of repose and internal friction, etc. While mixing fluid continuous and solid discrete media, a new continuous medium is formed – a suspension, properties of which differ from its constituents taken separately. Each particle of the fine solid phase in the fluid medium gets a liquid shell on its surface, resulting in a dipole formation with positive and negative charges. Dipoles orientation in the mixture volume is determined by interaction between them. As a result of this interaction, a structure is formed, and the suspension can be considered as a continuous medium. Under exposure of the volume of such a mixture to force F at the initial moment, the solvate shells of the dipoles are deformed and the initial shear stress τ_0 develops, which is the result of elastic deformation in this case. Then a shift of separate layers of the hydraulic fluid occurs with developing plastic viscosity. Such a mechanism of developing viscoplastic properties is typical of mixtures containing small and practically homogeneous particles.

CWF includes fine particles, though heterogeneous in size and shape. As a result, some solid particles will not be completely covered by the solvate shell or will lose it. During deformation of volume of such a suspension, viscoplastic friction is added to purely mechanical friction of the particles that have lost or have not got solvate shells on their surfaces. Viscosity in such mixtures manifests itself as a cumulative effect of plastic viscosity caused by resistance to shear of individual layers of the suspension and resistance to friction of solid particles that do not have solvate shells. Thus, development of viscoplastic properties in the volume of suspension is determined by both physical (formation of dipoles) and mechanical (friction) natures. According to this model, development of viscoplastic friction, arising resistance can be associated with some effective (apparent) viscosity [1].

The value of the viscosity coefficient depends on the value of structural viscosity, which is related to effective viscosity by the ratio:

$$\frac{\mu_{ef}}{\mu_{st}} = k_p,$$

$$\mu_p = \mu_{st} \cdot \frac{k_p}{k_{st}}. \tag{6}$$

The effective viscosity is an average viscosity value and a function of the average concentration of solid particles through the suspension flow cross section. Structural viscosity arises in plastic deformation of the suspension volume at the boundary of the flow nucleus. It is constant in its magnitude and has the greatest value. The effect of plastic viscosity arises at the suspension layers deformation, and its magnitude depends on structural viscosity (Fig. 2) [22].

Taking into account the peculiarities of developing viscoplastic properties by highly-concentrated fine fractional suspensions considered above, the Bingham model for them can be written as follows:

$$\tau = \tau_0 + \mu_p k_{st} \frac{\mathrm{d}v}{\mathrm{d}y}. \tag{7}$$

Or through structural viscosity:

$$\tau = \tau_0 + \mu_{st} \frac{k_p}{k_{st}} \cdot \frac{\mathrm{d}v}{\mathrm{d}y}. \tag{8}$$

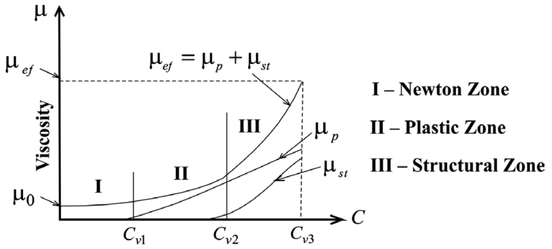

Fig. 2. Dependence of effective viscosity component on concentration of carbon particles in the hydraulic fluid: μ_{st} is structural viscosity; μ_{ef} is effective viscosity; μ_p is plastic viscosity; μ_0 is initial viscosity; μ is viscosity; C, C_{v1}, C_{v2}, C_{v3} are variants of concentration of coal particles in the hydraulic fluid

The latter one differs from the Bingham-Shvedov model by the fact that effective viscosity takes into account both structural and plastic properties of the deformable volume of the fluid (suspension).

The work makes an attempt to refine the rheological model of the state of non-Newtonian fluids, in which viscosity is considered as a function of the shear stress. Such a class of liquids includes coal water fuel, which depending on the properties, concentration and size of the solid component fractions can develop the properties of Bingham plastic, pseudoplastic and even thixotropic liquid.

As for multiparameter models, including the model of a rheologically complex medium (CWF), such a model is taken that reflects the nature of the change in a solid body under dynamic deformation:

$$\sum_{i=0}^{m} p_i \frac{\partial^i \tau}{\partial t^i} = \sum_{i=0}^{n} q_i \frac{\partial^i \varepsilon}{\partial t^i}, \tag{9}$$

where p_i is pressure in the i-th section of the hydraulic transport pipeline; q_i is the deformation component.

In this case, an option is considered when the transportation velocity is constant in time (stationary mode of transportation). Then the equation for the multiparameter model is written as follows:

$$p_0\tau+p_1\dot{\tau}=q_0\varepsilon+q_1\dot{\varepsilon}+q_2\ddot{\varepsilon}. \tag{10}$$

Having limited by three parameters, the general equation of the rheological model of coal water fuel has been obtained:

$$e+ig=\frac{[(e_m s+ce_0)(s+c)+e_m t^2+ict(e_m-e_0)]}{(s+c)^2+t^2}, \tag{11}$$

where $s+it$, $e+ig$ are complex numbers; s, t and e, g are normal and shear components of stresses and deformations respectively; e_m is the shear component at the boundary of the elastic region; e_0 is the boundary of the plastic region.

Thus, the shear stress, the shear velocity and viscosity of the water coal fuel are determined based on the formulas obtained, regardless of the type of liquids to which the researched system belongs.

The refined rheological model will be used as a basis for mathematical modelling of the flow of the coal water fuel in industrial hydrotransport systems, which will allow taking into account the rheological parameters of the CWF in solving the Navier-Stokes equations.

The flow of the coal water fuel in hydrotransport systems, as well as any other fluid, is described by the Navier-Stokes equations and the continuity equation, which, with respect to the motion conditions in pipes, transform into boundary layer equations.

When the self-similar flow mode of the coal water fuel in circular pipes is reached, taking into account the proposed rheological model, the Navier-Stokes equations in the cylindrical coordinate system will be written as follows:

$$u\frac{\partial u}{\partial x}+u_r\frac{\partial u}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho}\left[\frac{1}{r}\frac{\partial(\tau_{xr}r)}{\partial r}+\frac{\partial\tau_{xx}}{\partial x}\right],$$

$$u\frac{\partial v}{\partial x}+u_r\frac{\partial v}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+\frac{1}{\rho}\left[\frac{1}{r}\frac{\partial(\tau_{rr}r)}{\partial r}+\frac{\partial\tau_{rx}}{\partial x}\right], \tag{12}$$

$$\frac{\partial(ur)}{\partial x}+\frac{\partial(u_r r)}{\partial r}=0,$$

where x is the longitudinal axis of the pipe; r is the radius, measured from the axis of the pipe; u and u_r are the components of velocity along the axis and the radius of the pipe.

With respect to the case of the flow of the non-Newtonian fluid in circular pipes, after evaluating corresponding terms and discarding terms of the second order of smallness, we have obtained:

$$u\frac{\partial u}{\partial x}+u_r\frac{\partial u}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho r}\frac{\partial(\tau_{xr}r)}{\partial r},$$

$$u\frac{\partial v}{\partial x}+u_r\frac{\partial v}{\partial r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+\frac{1}{\rho}\left[\frac{1}{r}\frac{\partial(\tau_{rr}r)}{\partial r}+\frac{\partial\tau_{rx}}{\partial x}\right], \tag{13}$$

$$\tau_{rr}=2Z\frac{\partial u_r}{\partial r};\ \tau_{xr}=2Z\frac{\partial u}{\partial r};\ \dot{\varepsilon}=\left|\frac{\partial u}{\partial r}\right|.$$

The main difference of the system of equations from the case of the flow of the Newtonian fluid is associated with use of the proposed rheological model. As the result, the proposed equation generally does not go into the condition of constant pressure in the transverse direction at large Reynolds numbers, as in the case of the Newtonian fluid $n=m=1$, $\tau_0=0$.

In the case of the nonlinear viscoplastic fluid flow set in the coordinate x under the laminar flow mode, the equations are as follows:

$$0=-\frac{\mathrm{d}p}{\mathrm{d}x}+\frac{1}{r}\frac{\mathrm{d}(\tau_{xr}r)}{\mathrm{d}r}, \tag{14}$$

$$0=-\frac{\mathrm{d}p}{\mathrm{d}r}, \tag{15}$$

$$\tau_{xr}=\left[\tau_0^{1/n}+\left|\mu\frac{\mathrm{d}u}{\mathrm{d}r}\right|^{1/m}\right]^n. \tag{16}$$

It follows from equation (15) that the condition of constant pressure is fulfilled in the transverse direction.

Let us analyse the equations of motion under the turbulent flow mode, assuming that the nonlinear viscoplastic fluid is a homogeneous medium.

Having denoted time-averaged values of velocities u and v as u_0 and v_0, the pulsation components of the velocities as u' and v', pressure as p_0 and p', then after standard transformations the following system of equations has been obtained:

$$u_0\frac{\partial u_0}{\partial x}+u_{r0}\frac{\partial u}{\partial r}=$$
$$=-\frac{1}{\rho}\frac{\partial p_0}{\partial x}+\frac{1}{\rho}\left[\frac{1}{r}\frac{\partial(\overline{\tau}_{rx}-\rho\overline{u}'\overline{u}'_r)r}{\partial r}+\frac{\partial(\overline{\tau}_{xx}-\overline{\rho}u'^2)}{\partial x}\right],$$

$$u_0\frac{\partial u_{r0}}{\partial x}+u_{r0}\frac{\partial u_{r0}}{\partial r}=$$
$$=-\frac{1}{\rho}\frac{\partial p_0}{\partial r}+\frac{1}{\rho}\left[\frac{1}{r}\frac{\partial(\overline{\tau}_{rr}-\rho\overline{u}'^2_r)}{\partial r}+\frac{\partial(\overline{\tau}_{rx}-\overline{\rho}\overline{u}'\overline{u}'_r)}{\partial x}\right], \tag{17}$$

$$\frac{\partial(u_0 r)}{\partial x}+\frac{\partial(u_{r0}r)}{\partial r}=0.$$

The condition of constant pressure in the cross section of the flow is not met if the forces of plastic origin prevail over viscous and inertial forces. In all other cases, the condition of constant pressure in the cross section of the flow is roughly met.

6. Discussion of the research results of intensification processes in the transport pipeline

The main problems solved by intensification of processes in the transport pipeline are the following:

- increasing productivity, reducing energy consumption;
- increasing service life of pipelines and ancillary equipment;
- excepting particles degradation;
- improving sedimentation;
- expanding technological possibilities of application of pipeline transport.

Intensification of processes taking place in the mainline pipeline is carried out by impact of additional airstreams, oscillation, volume effect of these two factors on the moving mixture (Fig. 3, 4).

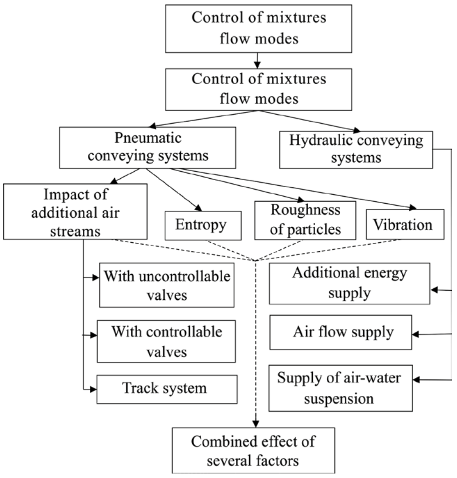

Fig. 3. An implementation scheme of intensification processes in pipeline transport

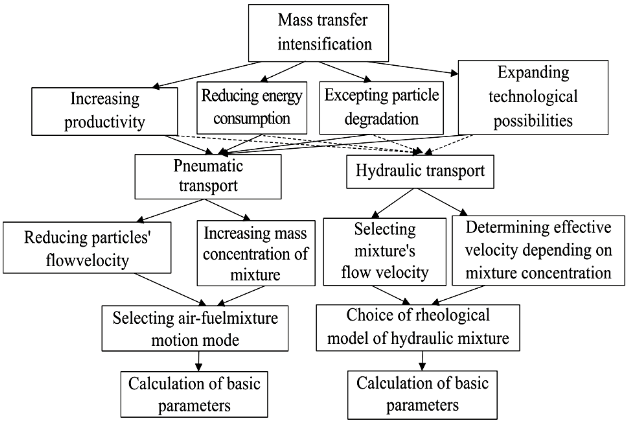

Fig. 4. A scheme for determining basic parameters of pipeline transport

Modes of mixtures flow and their phase transitions can be predicted and described using the concept of partial determinateness. Under the proposed approach, the observed process $y(t)$ acts as a determined (predictable) process when $|1-D| << 1$, as a random (unpredictable) process when $|D| << 1$ or a partially determined (partially predictable) process when $0 < |1-D| << 1$. In this case, D is the correlation measure of the forecast quality introduced as a normalized correlation function (correlation coefficient between observation and prediction):

$$D(\tau)=\frac{<y(t)z(t)>}{<y^2(t)><z^2(t)>^{0.5}}, \quad t=t_0+\tau. \tag{18}$$

Time of determined behaviour depends on fluctuation impacts on noise measurement system and defects in the model that is presented in the form of the following dependence:

$$\tau_{\text{det}}=F(v,f,\Delta M), \tag{19}$$

where ΔM is interpreted as inaccuracy of the model.

However, as in any physical system, during motion of gas-material flows in the pipeline transport, there are preserved unavoidable noises in the form of thermal processes, electrostatic forces, electromagnetic interference, interfacial effects, transformations of multicomponent media. These unavoidable fluctuation effects define limits of predictability. If $v \to 0$ and $\Delta M \to 0$, then the limit value (predictability horizon) is:

$$\tau_{\lim}=\lim \tau_{\text{det}}=F(0,f,0). \tag{20}$$

Predictability horizon $\tau_{\lim}$ characterizes time of dynamic system memory. At the same time, value $\tau_{\lim}$ characterizes time of reversible behaviour and is comparable to the information storage time during which the observed process loses information about noises effecting the system before. The concept of partial determinateness can be used in description of turbulent flows, as they have compatibility spatial domain [24]. In this case, randomness and determinism are not opposed to each other, but considered as poles of a single property – partial determinism.

7. Conclusions

1. Further development and improvement of pipeline transport are proposed to conduct on the basis of modern methodological approaches, based on the synergetic concept. It has been proved that transportation of bulk materials in transport pipeline under the influence of the carrying air flow may be regarded as an open system with its inherent characteristics. There has been made an assumption that constantly occurring non-equilibrium phase transitions in pneumatic conveying transport take place according to the scheme $O \leftrightarrow C$ (order – chaos), i.e. under the scheme of self-organization. There has been justified the hypothesis of occurrence of stochastic motion modes which arise while passing through intermittence, i. e. they are the result of collision of asymptotically stable and unstable motions of air-fuel mixtures flow. It has been established that flow of air-fuel mixtures with inner weaves and inner portion turbulent motions is considered as a process of self-organization with collective flows. At the same time, effective coefficients of transfer of momentum, force and mass of the moving material flow are determined.

2. It has been marked that rheological characteristics and hydraulic parameters of the CWF flow are influenced by the following factors:

– quality of the feedstock;

– concentration of the solid component, its granulometric composition;

– the type and amount of chemical impurities;

– the temperature and velocity modes.

3. It is established that the process of self-organization of mass transfer in the pneumatic transport pipeline is carried out by additional energy supply of the moving material flow. Energy supply is provided by the carrier gas, oscillation or combined action of several factors. Creation of additional vorticity of the flow is also facilitated by the shape and roughness of the particles and walls of the pipeline, turbulence of the bearing flow, entropy of the system, oscillation processes observed during movement of bulk materials in the transport pipeline.

4. There has been proposed the rheological model of the motion of non-Newtonian fluids, which takes into account the flow peculiarities, making it possible to determine the shear stress and viscosity of the CWF at different values of the shear velocity. The mathematical model of the CWF flow takes into account independent rheological parameters of the suspension,

which depend on concentration and granulometric composition of coal, as well as on the high-velocity modes of transportation.

5. It has been established that intensification of the processes occurring in the main pipeline is carried out by additional air streams and oscillations, volume effect of these factors, influencing the flowing mixture.

6. The main tasks have been determined, solved by intensification of processes in the transport pipeline:

– increasing productivity, reducing energy consumption;

– increasing the service life of pipelines and ancillary equipment;

– eliminating particle degradation;

– improving sedimentation;

– expanding technological opportunities for use of the pipeline transport.

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