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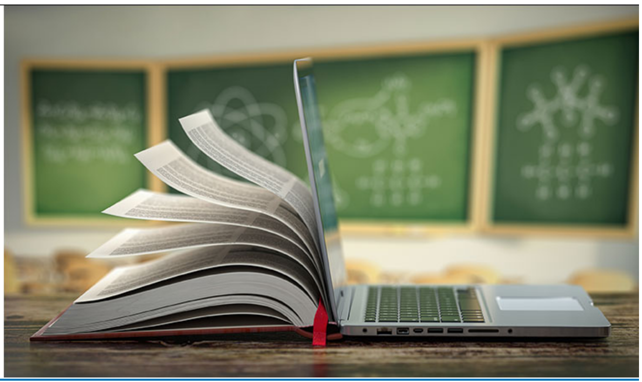

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Model of a turbulent flow of a two-phase liquid with an uneven distributed phase concentration in a horizontal pipe

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Abstract. We study the turbulent stationary motion of a mixture in a horizontal cylindrical pipe, taking into account the formation of a concentration field of the second dispersed phase that is not uniform over the cross section, and estimate the transporting ability of the flow. The article has developed a model for the movement of a two-phase mixture in a horizontal cylindrical pipe, taking into account the uneven distribution of the concentration of the second phase over the flow ... Also, in this model of mixture motion, the coefficient of the force of interaction between the phases is determined depending on the concentration distribution. The problem is solved by a numerical method. Investigating the numerical results of the problem, the nature of the formation of the velocity field at various values of the flow saturation with solid particles is revealed and makes it possible to assess the account of the size of these particles, taking into account the turbulence of the flow. The implementation of the developed mathematical models and recommendations will make it possible to predict the transporting ability of a two-phase flow in pressure systems, and helps to find solutions with spatial hydrotransport and irrigation and drainage systems.

When studying the nature of the movement of suspended particles, the most relevant direction is the study of the transport of suspended particles in pipelines. To ensure the reliability of design, construction and efficient operation of hydrotransport systems, it is necessary to study the regularities of the movement of a two-phase flow.

In order to prevent siltation in pipelines, it is necessary to study the transporting ability of the flow, which is associated with the establishment of a regularity in the distribution of the concentration of phases over the flow cross section.

In this aspect, the study and analysis of regularities describing the movement of solid particles along horizontal pipelines, generalization of experimental and field data, the development of perfect calculation models that take into account all factors and processes characterizing the movement of a suspended flow in pressure pipelines is an urgent task in solving the problem of transport and regulation of movements along pipelines.

It is known from the literature that the turbulent regime of motion prevails in the mixture flows [1], [2]. The introduction of solid particles into a homogeneous fluid flow can significantly affect its turbulent characteristics. In the general case, the introduction into a liquid flow of solid particles having a higher density than the density of the liquid causes an asymmetry in the distribution of averaged velocities over the flow section.

The effect of solid particles on the turbulent characteristics of the flow is assessed by many researchers in different ways. Most researchers believe that particulate matter dampens high-frequency pulsations or smoothes out flow turbulence.

In this paper, we consider a two-dimensional model of two-phase flow for the numerical simulation of two-phase fluid flows, based on the equations of the model of motion of interpenetrating media for a one-velocity continuum, taking into account turbulence.

Thus, we will consider a stationary turbulent motion of a two-phase mixture in a horizontal cylindrical pipe, taking into account the non-uniform distribution over the cross section of the concentration field of the second - dispersed phase, while further evaluating the throughput of the pipeline.

Determination of the distribution of the averaged longitudinal velocity component over the cross-section of the flow of multiphase media along horizontal cylindrical pipelines is one of the most difficult and unsolved issues in the mechanics of multiphase media.

There are a number of theoretical works where, along with the profiles of the averaged longitudinal velocity, some other parameters of hydrotransport are determined. An overview of work on the movement of multiphase media is given in [3],[4], [5].

However, these works consider:

- either a uniform concentration distribution or an implicit influence of the flow rate on the change in the concentration of the transported medium;
- the phase interaction coefficient is taken as a constant value;
- for a circular horizontal pipe, the problems are reduced to an axisymmetric form or separate flows are considered.

The non-uniformity of the concentration distribution significantly complicates the solution of the differential equations of motion in comparison with a similar problem for axisymmetric flows. In this regard, many researchers limited themselves, as a rule, to the construction of a profile of averaged velocities.

The question of constructing a velocity profile for the conditions of a pressure head suspended flow, taking into account the uneven distribution of concentration along the vertical, is poorly studied and is of scientific and practical interest.

Thus, the problem is to determine the longitudinal velocities of the phases and the concentration distribution, for given parameters of hydrotransportation, such as the volume concentration of solid particles in the flow, their particle size distribution, the average linear size and hydraulic size of these particles, the density and viscosity of the phases for the movement of a two-phase mixture along round horizontal cylindrical pipe with diameter D.

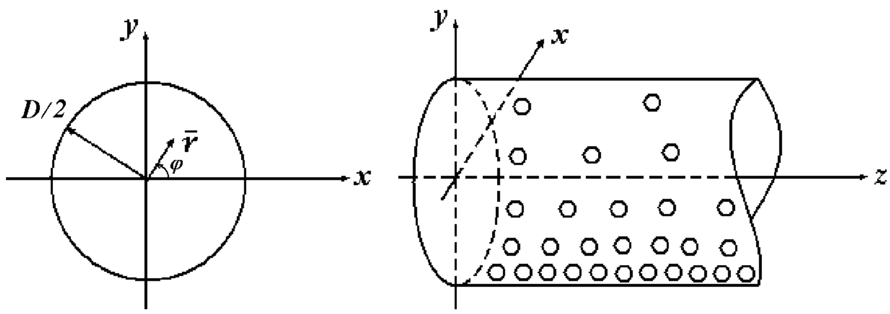

Figure 1. Schematic representation of the coordinate systems used.

Let us consider the steady motion of the slurry along a circular horizontal cylindrical pipe (figure 1). In this case, the slurry is highly concentrated and the concentration distribution is uneven along the height and is a function of r and φ, and the solid particles included in the mixture are the same in density.

Based on the model of motion of interpenetrating media, the differential equations of a two-phase mixture in a cylindrical coordinate system have the form [6]:

$$\left.\begin{aligned} & f_n \frac{\partial p}{\partial z} = \frac{\mu_n}{r}\frac{\partial}{\partial r}\left(r f_n \frac{\partial u_n}{\partial r}\right) + \frac{\mu_n}{r^2}\frac{\partial}{\partial \varphi}\left(f_n \frac{\partial u_n}{\partial \varphi}\right) + K\left(u_{\frac{2}{n}} - u_n\right), \\ & f_n \frac{\partial p}{\partial r} = 0, \\ & f_n \frac{\partial p}{\partial \varphi} = 0, \end{aligned}\right\} \quad (1)$$

where;

$\frac{\partial p}{\partial r}$, $\frac{\partial p}{\partial \varphi}$ и $\frac{\partial p}{\partial z}$ – pressure gradient components;

u_{nr} , $u_{n\varphi}$, u_{nz}- components of the velocity vector of each phase;

f_n - phase concentrations;

μ_n - phase viscosity coefficient;

K - force coefficient of interaction between phases.

Here and in what follows, when n = 1, we mean the parameters of the first - carrier (liquid) phase, and when n = 2, we mean the parameters of the transported (solid) phase.

From the differential equations of motion (1) we have that the pressure drop is a function of only the coordinate z and does not depend on r and φ, i.e.

$$\frac{\partial p}{\partial z} = \frac{dp}{dz} .$$

To the differential equations of motion (1) we add the relations between the phase concentrations

$$f_1 + f_2 = 1; \quad (2)$$

adhesion boundary conditions at $r = R$:

$$u_1 = 0, \qquad u_2 = 0 \quad (3)$$

and the condition of symmetry of the vertical axis (y), i.e. at $0 \leq r \leq R$ and $0 \leq \varphi \leq 2\pi$:

$$u_n(r,\varphi) = u_n(r,\pi-\varphi), \quad u_n(r,\pi+\varphi) = u_n(r,2\pi-\varphi), \quad . \quad (4)$$

The concentration distribution of the second phase is determined by the formula:

$$f_2 = f_{20} exp\{(-\frac{3(\rho_ч - \rho)g}{\rho_ч u_1^2})(R + r sin\varphi)\} \quad (5)$$

which is obtained on the basis of the statistical Maxwell distribution law for the weighted layer [7],[8] and [9].

The coefficient of the force of interaction K between the phases is determined by the formula [8], [9] and [10]:

$$K = K_1 f_1^{\beta} \quad (6)$$

From the differential equation of motion (1) it is seen that the velocities of the phases of the mixture depend on the distribution of the concentration f2 and the interaction ratio K. At the same time, these parameters depend on the distribution of the velocities of the mixture. Thus, a closed system of nonlinear differential equations was obtained to study the motion of a two-phase mixture with an uneven concentration distribution.

Experiments show that, the main mode of motion of a mixture of liquid and solid particles is turbulent. Therefore, the kinematic structure of suspended streams is closely related to turbulence and especially with physical phenomena that occur in homogeneous fluid flows with developed turbulence.

Differential equations of motion (1), taking into account the turbulent characteristics, can be written according to the model [8], [9] and [10] as follows:

$$f_n \frac{dp}{dz} = \frac{\mu_n}{r}\frac{d}{dr}\left(r f_n \frac{du_n}{dr}\right) + \frac{\mu_n}{r^2}\frac{d}{d\varphi}\left(f_n \frac{du_n}{d\varphi}\right) + K\left(u_{\frac{2}{n}} - u_n\right) - L_n u_n. \tag{7}$$

Here L_n- turbulent exchange ratio [5].

Turbulent viscosity is defined as

$$\mu_n^T = \rho_n \chi \left(\sqrt{R^2 - r^2}\right)\left(\frac{\partial u_n}{\partial y}\right)^2 + \mu_n \tag{8}$$

χ - dimensional constant obtained experimentally.

With this choice, the turbulent viscosity coefficient is a function of the coordinate and flow rate. To determine the kinematic nature of the turbulent flow of the mixture, differential equations (7) with additional equations and boundary conditions (2) - (6) and (8) are solved numerically.

For this, we rewrite the differential equations of stationary motion of the two-phase mixture (10) in dimensionless form. Introducing dimensionless parameters:

$$\bar{r} = \frac{r}{R} \quad and \quad \bar{u} = \frac{u_z}{U}$$

where R - pipe radius;

U - characteristic speed;

Then we have for $0 \le r \le R$(or $0 \le \bar{r} \le 1$) and $0 \le \varphi \le 2\pi$

$$\frac{f_n}{U}\frac{R^2}{\mu_n}\frac{dP}{dz} = \frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\bar{r} f_n \frac{\partial \bar{u}_n}{\partial \bar{r}}\right) + \frac{1}{\bar{r}^2}\frac{\partial}{\partial\varphi}\left(f_n \frac{\partial \bar{u}_n}{\partial\varphi}\right) + \frac{K_1 f_n^{\beta} R^2}{\mu_n}\left(\bar{u}_{\frac{2}{n}} - \bar{u}_n\right) - L_n \bar{u}_n \quad \text{(n=1,2)} \tag{9}$$

No-slip condition (6) in dimensionless variables has the form:

$$\bar{u}_1 = 0,\ \ \bar{u}_2 = 0 \text{ at } \bar{r} = 1. \tag{10}$$

To these conditions is added the symmetry condition (4) along the vertical axis (y).

Task (9) - (10) with considering (5), (6) and (8) solved by the numerically - finite-difference method, on a grid $w_r \bigcup w_{\varphi}$:

- by variable r - uniform mesh with a step h_r

$$w_r = \left\{ \bar{r}_i = (i + 0.5)h_r;\ i = 0,1,2,\ldots,N;\ h_r = \frac{R}{0.5 + N} \right\}, \tag{11}$$

- by variable φ - uniform mesh with a step h_φ

$$w_\varphi = \left\{ \varphi_j = j h_\varphi;\ j = 0,1,2,\ldots,M-1;\ h_\varphi = \frac{2\pi}{M} \right\}.$$

Excluding points with a coordinate $\bar{r} = 0$ from the number of grid points, we save ourselves from the need to approximate the equation at $\bar{r} = 0$, but we create a problem of approximating the equation (11) at .$\bar{r} = \frac{h_r}{2}$.

From the numerical analogs of equations (11), which are obtained by the balance method, using the average value for the coefficients r and φ, as well as the central differences for derivatives, makes it possible to obtain an explicit expression for determining u_{nij} and u_{n0j} (at $r=h_r/2$)

The resulting finite difference equations for u_{nij} and u_{n0j}, together with the adhesion and symmetry conditions, as well as the proposed two-phase flow model, are solved by the iterative method - the upper relaxation method. Convergence of the iterative relaxation method for the relaxation parameters $w<2$ for elliptic equations is proven in many literatures on computational mathematics.

The calculations were carried out for various numbers of nodal points along the radius and arc of a circle (for example: 4x6, 4x8, 4x8, 10x8, 10x16, 10x20, 10x24, 12x20, 6x16, 16x22 …). Calculations have shown that, starting with a grid with 11x16 nodal points, an increase in the number of grid nodes does not significantly affect the calculation results. Thus, for further calculations, we select the nodal points along the radius of 11, and along the arc of a circle -16 (i.e.11x16).

An analysis of the numerical results shows that the shape of the longitudinal velocity distribution diagram along the vertical section depends significantly on the volumetric content, size and density of the second phase.

Numerical experiments were carried out to determine the velocity profile of the two-phase mixture with the values of the parameters dp/dz=-1,5; dp/dz=-2; μ_1=0.0001 кГс/м^2; K_1=500; d_i/d_0=1 for different values of the volumetric content of the second phase.

The asymmetric nature of the flow is pronounced in the area where 2400<Re<3200. Numerical results show that the amount of displacement depends on the concentration, density and size of the solid particles. For small and relatively light particles, there is practically no displacement.

With an increase in the modulus of pressure drop, respectively, at Re> 3800, the maximum velocity - the velocity profile tends to the geometric axis of the pipeline and the deformation in the lower part is smoothed out, i.e. the velocity profile tends to the shape of a single-phase liquid.

Thus, with an increase in the volumetric content of the concentration of the second phase, at $\rho_2>\rho_1$ and $\mu_2>\mu_1$ the speed of movement of both phases decreases.

The obtained numerical results are in qualitative good agreement with the experimental data [1], [9], etc., while the maximum error in comparing theoretical and field data does not outweigh 17% depending on the values of the coefficients K, χ and L.

Numerical results for different values of pressure drop in the form of a velocity diagram are shown in figure 2.

Based on the analysis of the results of numerical studies in a turbulent mode of movement of a two-phase mixture along a cylindrical horizontal pipeline, it was established that:

- theoretical calculations are in good agreement with experimental data, the distribution diagram of longitudinal velocities along the vertical section of the flow has an asymmetric character, i.e. with a variable distribution of phase concentration, the location of the maximum phase velocity is displaced upward from the geometric axis of the pipeline;
- with an increase in the pressure drop modulus, the velocity profile tends to the shape, as in a single-phase liquid, and the maximum velocity increases, i.e. the flow capacity increases.

The results obtained in this work, which consist of calculation methods, an algorithm for their numerical implementation and graphs, can be used in the further study of the nature of multiphase flow, design, construction and operation of hydrotransport systems, as well as for predicting the transporting capacity of the flow in pipelines.

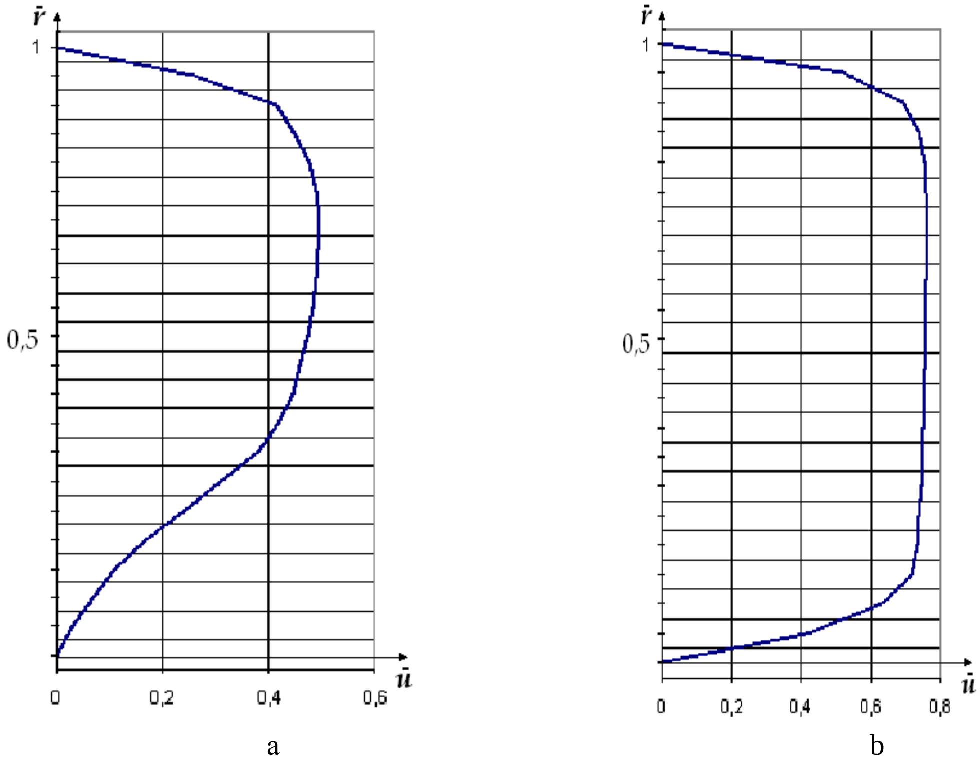

Figure 2. General view of the longitudinal velocity diagram with turbulent flow. a)$\frac{\partial p}{\partial z}$ = -1,5 and b)$\frac{\partial p}{\partial z}$ = -2.

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