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# Determination of the formation model of the phase concentration field along the section of the turbulent flow of hydrotransport using information technologies

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# Determination of the formation model of the phase concentration field along the section of the turbulent flow of hydrotransport using information technologies

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**Abstract**. The problem of increasing the reliability and durability of hydrotransport facilities is one of the most important national economic tasks. The formation of the concentration field of the second dispersed phase, which is nonuniform over the cross section, is studied by the turbulent stationary motion of the mixture in a horizontal cylindrical pipe and the transporting ability of the flow is estimated. The article proposed a mathematical model and a method for calculating the concentration field of solid particles along the depth of the flow using information technologies, where the formation of the concentration field is first determined through the size of solid particles when a two-phase mixture moves in a horizontal cylindrical pipe. 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 using the integrated system for mathematical calculations MathCAD. Investigating the numerical results of the problem, the nature of the formation of the concentration field at various values of the saturation of the flow with solid particles and which makes it possible to estimate 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 help to find solutions for spatial hydrotransportation and irrigation and drainage systems.

## 1. Introduction

The level of development of hydrotransport imposes increased requirements on the quality of design and operation of installations, since in conditions of increasing throughput and transportation distance, non-optimal parameters of the system will lead to significant economic losses. Because of this, the study of the distribution of the velocity, turbidity and size of solid particles along the depth and length of the suspended flow or during hydrotransport has long attracted the attention of researchers. A more accurate solution of these questions, even in a one-dimensional formulation of the problem, would open up new possibilities for further understanding the structure of turbulent suspended flows.

Currently, there are practically no methods for determining the reliability function of both designed and operated hydrotransport systems, taking into account the specifics of these objects and the stochastic processes occurring in them.

The question of the distribution of the concentration of solid particles over the cross section of the flow is of great importance when applying the theory of motion of a two-phase medium to flows carrying dispersed particles, which can be considered as a heterogeneous mixture.

A large number of works have been carried out using the theory of multiphase flows in the direction of determining the law of distribution of dispersed particles in the field of gravity and velocities of the carrier medium.

The issue of mathematical modeling of processes is considered in various fields of science: geodynamics (application to Sciences of Earth) [1-3], data analysis [4-19], mechanics [20-21], physics and chemistry of polymers and nanotechnology [22-24]. The given article proposes a mathematical model and a method for calculating the concentration field of solid particles along the depth of the flow, where the coefficient of the force of interaction between the phases is determined depending on the concentration distribution.

A review of the literature [25-27] on the study of the motion of multiphase media shows that the most widespread in the field of studies of two-phase flows in a carrier fluid and solid particles are semi-empirical theories: diffusion [28] and gravitational [29]. Many researchers have developed these theories when studying the distribution of the concentration of dispersed particles in molasses liquid.

A feature of the model of suspended flows, proposed in [29], is accounting the force of phase interaction, which is necessary when describing the nature of two-phase flows. S.I. Kril [30], with a view of more fully describing the motion of suspended particles, adheres to the discrete concept, which allowed him to obtain a more simplified form of differential equations. However, the solution of the obtained equations requires additional dependencies.

## 2. Materials and methods

Given the randomness and chaotic of the movement of suspended particles in the flow, some researchers used the methods of statistical physics to describe the movement of solid particles [28; 31-33].

The studies of the authors of the above method indicate a change in the parameters ($\rho$, $\chi$, m, d, etc.) included in the formula for the distribution of velocities over the depth of the flow in a wide range. And this limits the scope of the obtained formulas for the concentration distribution. In addition, the analysis of the formulas for the concentration distribution along the flow depth obtained by the above scientists gives contradictory conclusions, which are noted in the work [28].

The main reason for the limited practical application of the above theories is not a closed system of differential equations and neglect of the effect of the transported phase on the velocity distribution, but it is of no small importance in studying the laws of the nature of a two-phase flow.

The model of motion of interpenetrating mixtures by Kh.A. Rakhmatullin [34] made it possible to obtain a closed system of equations of motion, with the help of which it is possible to theoretically study many phenomena occurring in a mixture during its motion. K.Sh.Latipov [35-37] applied this theory to the conditions of turbulent flow and obtained dependences confirmed by experimental data.

## 3. Results

Proceeding from the continuity equation for the second phase and replacing the combination of a number of parameters with the parameter $\alpha$, one can obtain a formula for determining the concentration distribution in an exponential form:

$$f_2 = f_{20} e^{-\alpha y} \tag{1}$$

where $f_{20}$ - concentration of the second phase at the bottom of the stream. However, here we do not analyze the nature of $\alpha$ ratio.

Due to the great complexity of the processes occurring during the hydrotransportation of solid materials through horizontal pipelines, there is a very limited number of theoretical works devoted to the issue of the distribution of suspended matter concentration along the vertical pipe diameter. The need to take into account the size distribution along the flow depth when deriving the calculated dependencies noted in [38-39], greatly complicates the study of the hydrotransportation of solid materials.

Thus, on the basis of the performed analysis, it can be noted that the possibilities of successful application of the formulas of the above works to calculate the distribution of phase velocities, concentration and size along the flow depth during hydraulic transport in pipelines are limited. In addition, the circular cross-section of the pipeline makes it much more difficult to study the movement of a two-phase flow.

A completely different approach to determining the concentration distribution law is used in pseudo-liquefied flows. N.I. Syromyatnikov [32], based on the convergence of the random motion of particles in a suspended layer under the influence of hydrodynamic forces of the flow and the forces of the gravitational field with the thermal motion of gas molecules, as a result of processing experimental data, proposed a calculation formula for the concentration distribution, reminiscent of the barometric formula of molecular kinetic theory of gases

$$n = n_0 e^{-By} \tag{2}$$

where n – the number of particles at a certain height y;

$n_0$ – number of particles at zero level;

B – coefficient proportional to the kinetic energy of moving particles.

B.A. Fidman [38], applying dependence (1) for the case of distribution of solid particles in a liquid flow in a cylindrical pipe, shows the possibility of applying the molecular-kinetic theory for the case of suspended flows.

Let us consider the distribution of the concentration of discrete particles along the depth of the flow in the gravity field under the influence of the Archimedes force and the force of interaction between the phases.

According to the approach of molecular kinetic theory, the concentration distribution of the *i*-th fraction in the gravity field has the form [26; 35; 40; 41]:

$$f_{2i} = f_{2i0}\exp\left[\left[-\frac{3(\rho_{ri}-\rho)g}{\rho_{ri}u_i^2}+\frac{3}{2}\rho C_0\frac{S_{ri}w_{ri}^2}{m_{ri}u_i^2}\right](h-y)\right] \tag{3}$$

where $f_{2i0}$ - concentration of *i*-particle fraction at y=0;

$\rho_r$, $\rho$ - bulk densities of *i*- fractions and liquids;

$u_i$ - longitudinal speed of *i*-fraction;

$m_i$ - true density of *i*- fraction;

$S_{ri}$ - cross-sectional area of *i*- fraction;

$C_0$ - drag coefficient;

$w_{ri}$ - hydraulic size.

In the case of a circular cylindrical pipe, passing to cylindrical coordinates, we have:

$$f_{2i} = f_{2i0}\exp\left[\left[-\frac{3(\rho_{ri}-\rho)g}{\rho_{ri}u_i^2}+\frac{3}{2}\rho C_0\frac{S_{ri}w_{ri}^2}{m_{ri}u_i^2}\right](R+r\sin\varphi)\right]. \tag{4}$$

Starting from a certain fraction with a $d_0$ diameter and $m_{r0}$ mass, the role of gravity becomes much less than the force of flow resistance. As a result, in this range of parameters, the size of the fraction has practically no effect on the concentration distribution. Therefore, to establish the effect of the size of fractions, the concept of the optimal diameter is introduced. Based on the equality of the kinetic energy of the flow of the carrier fluid and the solid particle [25; 26], it apply:

$$\Theta = \frac{2m_{ri}u_i^2}{3} = \frac{2m_{r0}u^2}{3} \tag{5}$$

where $m_{r0}$ - the mass of a particle whose velocity is equal to the average flow velocity $u$;

$m_{ri}$ - mass of $i$-particle, which speed differs from the average flow rate. Assuming that the particles are spherical, for i-fraction we have:

$$u_i^2 = u^2\left(\frac{d_0}{d_i}\right)^3 \tag{6}$$

Taking into account (5), for the volume concentration distribution we have the following formula:

$$f_{2i} = f_{2i0}\exp\left[\left[-\frac{3(\rho_{ri}-\rho)g}{\rho_{ri}u_i^2}+\frac{3}{2}\rho C_0\frac{S_{ri}w_{ri}^2}{m_{ri}u^2}\right]\left(\frac{d_i}{d_0}\right)^3(R+r\sin\varphi)\right] \tag{7}$$

Particle with $d_0$ diameter, the speed of which is equal to the average flow rate, we will call the "optimal particle". The distribution of "optimal particles" along the flow depth will be considered "normal" if it obeys an exponential law. The diameter of this particle will be called the “optimal diameter”. From the condition of equilibrium between the force of gravity and the force of resistance, we determine the "optimal diameter" in the form:

$$d_0 = \sqrt{\frac{18\mu u\sin\alpha}{g(\rho_r-\rho)}} \tag{8}$$

- for free-flow movement and in the form:

$$d_0 = \sqrt{\frac{18\mu u\frac{dp}{dz}}{\gamma g(\rho_r-\rho)}} \tag{9}$$

- for pressure movement.

Thus, the obtained formula for determining the concentration distribution (6) differs from the existing ones in that, first, the molecular kinetic theory is used; second, the main parameters characterizing suspended particles are taken into account ($d, C_0, \rho_0, \rho$) and depending on the flow rate.

Thus, the task is to determine the distribution of the concentration of phases, 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 a circular horizontal cylindrical pipe with D diameter.

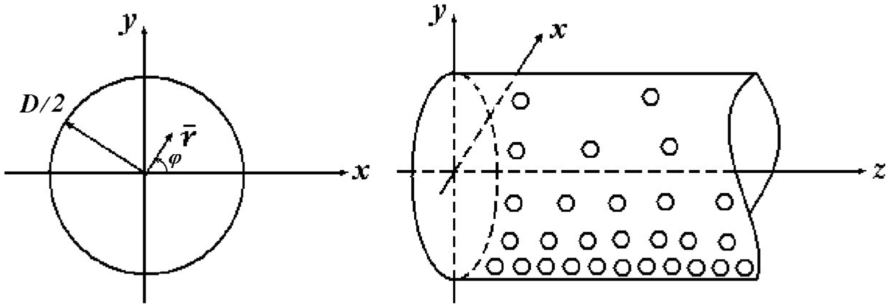


**Figure 1.** Schematic representation of the coordinate systems used.

Consider the steady motion of the slurry along a circular horizontal cylindrical pipe (figure 1). In this case, the concentration distribution is uneven along the flow depth and is a function of $r$ and $\varphi$, and the solid particles included in the mixture are the same in density.

Based on the model of motion of interpenetrating media [34], the differential equations of motion of a two-phase mixture in a cylindrical coordinate system, taking into account turbulent characteristics and uneven distribution of phases over the depth of the flow, we write according to the model [25], [26], [35] and [36] as follows:

$$f_n \frac{dp}{dz} = \frac{\mu_n}{r}\frac{d}{dr}\left(rf_n \frac{du_n}{dr}\right) + \frac{\mu_n}{r^2}\frac{d}{d\varphi}\left(f_n \frac{du_n}{d\varphi}\right) + K\left(u_{\frac{2}{n}} - u_n\right) - L_n u_n. \tag{10}$$

where:

$\frac{\partial p}{\partial r}$ - pressure gradient components;

$u_n$ - longitudinal component of the velocity vector of each phase;

$f_n$ - phase concentrations;

$\mu_n$ - phase viscosity ratio;

$K$ - ratio of force of interaction between phases;

$L_n$ - turbulent exchange ratio [36].

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.

To the differential equations of motion of a two-phase flow (9), we add the relations between the phase concentrations:

$$f_1 + f_2 = 1 \tag{11}$$

adhesion boundary conditions at $r = R$ :

$$u_1=0, \qquad u_2=0 \tag{12}$$

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

$$u_n(r,\varphi) = u_n(r,\pi-\varphi),\ u_n(r,\pi+\varphi) = u_n(r,2\pi-\varphi), \tag{13}$$

The concentration distribution of the second phase is determined by the formula (6), which is obtained on the basis of the statistical Maxwell distribution law for the suspended layer [32], [35] and [36].

The coefficient of the force of interaction K between the phases is determined by the formula [25], [26] and [41]:

$$K = K_1 f_1^{\beta} \tag{14}$$

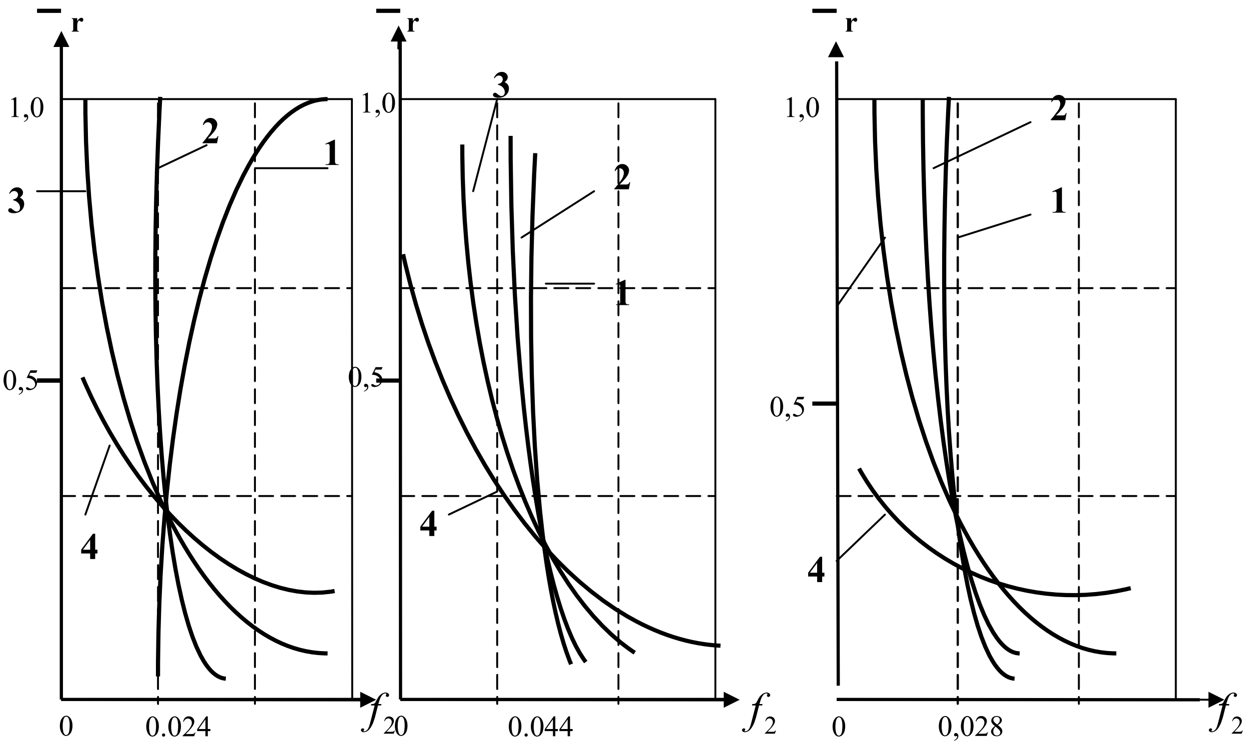
Thus, to study the non-uniform distribution of concentration over the cross-section of the flow, a closed system of nonlinear differential equations was obtained.

## 4. Discussion

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 to physical phenomena that take place in flows of a homogeneous fluid with developed turbulence and in this model is taken into account based on the work [36].

To determine the distribution of the concentration of phases over the depth of the turbulent flow of the mixture, the differential equations of motion of the mixture (9) are solved taking into account the formula for the distribution of the concentration of phases (6), additional equations (8), (10), (13) and boundary conditions (11), (12), numerically on dimensionless coordinates.

Based on numerical experiments, Fig. 2a shows the concentration distribution diagrams depending on the change in the true phase densities. It can be seen from the figures that at $\rho_r/\rho=1$ that is, at the same densities of the liquid and the transported material, a more uniform concentration distribution is obtained. And for values $\rho_r/\rho>1$ (when the density of the conveyed material is greater than the density of the liquid), the concentration distribution becomes uneven. It can be seen from the concentration distribution plot that with increasing of $\rho_r/\rho$ the concentration of the second phase, due to redistribution, rapidly decreases in the upper part of the flow, increasing in the lower part.



a) b) c)

**Figure 2.** Curves of concentration distribution along the vertical in depending on density, viscosities of phases and particle size:
a) 1-$\rho_r/\rho$ =0,5; 2-$\rho_r/\rho$= 1; 3-$\rho_r/\rho$=1,5; 4-$\rho_r/\rho$= 2;
b) 1- $\mu_2/\mu_1$ = 0,05; 2- $\mu_2/\mu_1$ =0,1; 3- $\mu_2/\mu_1$ =1,0; 4- $\mu_2/\mu_1$ =10;
c) 1- $d_1/d_0$ = 0,5; 2 - $d_1/d_0$ =1; 3- $d_1/d_0$ =1,5; 4- $d_1/d_0$ =2.

For example, for $\rho_r/\rho=1,5$ the relative content of the second phase not only decreases in the upper part, but even in the central parts of the stream, about 20% of the total mass of the second phase remains. For $\rho_r/\rho$=2 in the central part of the stream, about 5% of the mass of the second phase remains. And when $\rho_r/\rho$ =2,5 the bulk mass (i.e. 90%) of the second phase is located in the lower part of the pipeline: precipitation of particles occurs, i.e. solid particles begin to fall out onto the lower wall of the pipe, and the critical mode of motion begins. Hence, we can conclude that when transporting solid particles of lower density, we can expect a more uniform distribution of concentration along the depth of the flow. Concentration distribution plots for different values $\rho_r/\rho$ also intersect at a certain distance from the bottom of the pipeline, corresponding to the average concentration of the second phase, which corresponds to the experimental data [25; 30; 42].

Similar concentration distributions were obtained for different values $\mu_2/\mu_1$ and $d_1/d_0$, which are shown in figures 2b and 2c. Comparison of the numerical results (figures 1b and 1c) with the data of experimental works [25; 30; 38; 42] show that an increase in the coefficient $\mu_2$ in theoretical calculations corresponds to an increase in the particle size in the experiment.

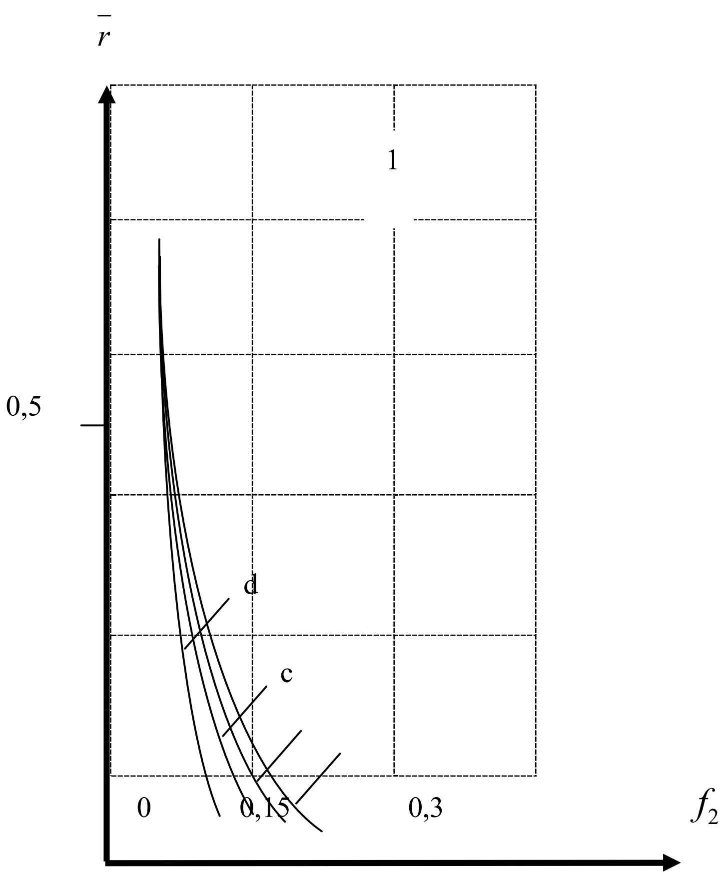


**Figure 3.** Distribution of the concentration of the second phase along the depth of the flow at different volumetric values $f_2$: a) 0,044; b) 0,035; c) 0,024; d) 0,018.

Figure 3 shows the results of calculating the concentration distribution versus the volumetric content of the second phase, where with an increase in the concentration of the second phase, its volumetric content increases only in the lower part of the pipeline at $\rho_r > \rho$. But the weighing ceiling remains constant. As soon as 90 or more percent of the transported particles are contained in the lower part of the stream, the critical mode of motion begins. To get rid of the critical mode of movement, it is necessary to increase the average flow rate.

## 5. Conclusion

In conclusion, the following conclusions can be drawn:

- An equation for the concentration distribution over the vertical section of the mixture flow in a cylindrical coordinate system is obtained, taking into account the size of solid particles for the theories of two-phase flow motion.
- Verification and assessment of the adequacy of the proposed dependencies were made by comparing and comparing the calculated values with the experimental data of a number of authors. The results of checking the proposed calculation methods showed their practicality and a small error (8-10%).
- The results obtained in the work, which consist of calculation methods, an algorithm for their numerical implementation, graphs and training materials, can be used in the design, construction and operation of hydrotransport systems, as well as for predicting the transporting capacity of a stream in pipelines.

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