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SOME RESULTS OF EXPERIMENTAL AND THEORETICAL MODELING OF HYDROTRANSPORT OF HIGH DENSITY BULK MATERIALS

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Abstract: The results of experimental studies of dynamic and kinematic parameters of very dense particulate materials (in particular, cooper powder of density $\rho_s > 8\,000$ kg/m^3) materials pipeline hydraulic transport are presented. The previously developed method for calculation of the main parameters of hydraulic transport of dense solids particles was summarized and tested, and it was found that the proposed mathematical models can be successfully applied not only for a wide class of suspensions, but can also serve for calculation of the high-pressure and traditional pneumatic pipeline systems.

KEY WORDS: dense solids, pressure gradient, critical velocity, hydraulic and pneumatic transport

1. INTRODUCTION

Recently, a great interest has been taken to hydrotransport of rather dense disperse materials with density even higher than $\rho_s > 8000$ kg/m^3. Unfortunately, there are practically no bibliography data on this question. Therefore, it is quite obvious that to elaborate a practical guidance for calculation of the parameters of the pipeline hydrotransport of such materials, additional studies need to be performed. Further, it is necessary to compile the bibliography data and carry out new experimental and theoretical studies.

The basic parameters of pipeline transport systems are hydraulic resistances and critical velocities, which are closely related to the flow kinematic structure, especially the concentration and velocity distribution in the slurry flow. To develop a science-based methodology for calculating these parameters, the distribution laws for local mean concentration and flow velocity over the pipe cross section, and the master curves of hydraulic resistances and critical velocities should be defined.

2. COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

Based on heterogeneous two-phase flow equations Kril and Berman (2000) solved the problem of concentration and mean slurry velocity distribution. The unknown initial parameters entering to these relationships were determined from special auxiliary experiments, and found formulas for distribution of concentration and mean velocity were successfully used for calculating hydraulic resistances and critical velocities of materials with density $\rho_s \leq 4000$ kg/m^3.

These relationships for the pressure gradient I and the critical velocity V_{cr} can be represented as:

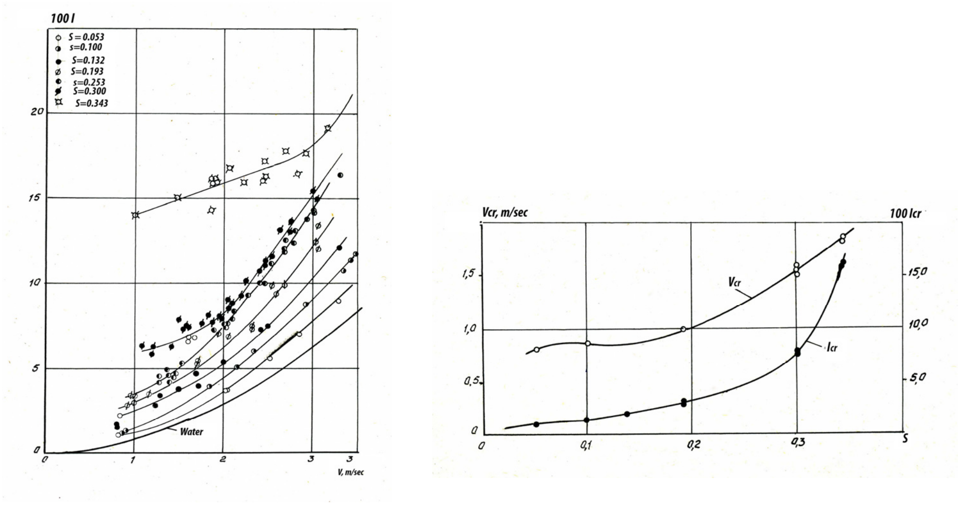
$$I = \frac{\rho_0}{\rho_W} \frac{\lambda}{(1-a)\omega^2} \frac{V^2}{2gD} + (\Delta_S - 1) S \frac{W_S}{V} (1-S)^n \varphi \tag{1}$$

$$V_{cr} = \left(\frac{D}{D_*} \right)^m \alpha \frac{(\mathrm{Re}_*^{1/8} + 0.791) V_f}{\mathrm{Re}_*^{1/8} + 0.791 \beta_*} \tag{2}$$

$$V_f = 3.94 \left[\frac{k_0 \sigma (\Delta_S - 1) S_m h_{cr}}{1 + a_{cr}} \right]^{4/7} \cdot \frac{(1 - a_{cr})^{5/7} g^{4/7} D_*^{5/7}}{((\rho_0 / \rho_W)_{cr}^3 \psi_0)^{1/4} \upsilon^{1/7}} \tag{3}$$

where ρ_o - averaged suspension density at the top of pipeline; ρ_s - density of solids; ρ_w- density of carrier liquid; λ - hydraulic resistance factor; α and ω - parameters of axial asymmetry of the velocity field; n - semi-empirical coefficient (function of Reynolds number of solid particles); V - averaged flow velocity; g - gravity acceleration; D - internal pipe diameter; $\Delta_s = \rho_s / \rho_w$; W_s - mean solids settling velocity; S - averaged volumetric concentration; φ - parameter of concentration distribution; $D_* = 0.1$ m - reduced pipe diameter; $\mathrm{Re}_* = V_f D_* / \upsilon$ - the Reynolds number, υ - kinematic viscosity of carrier liquid; k_o - solids friction factor; σ - rate of k_o reduction due the presence of powdered solid fraction; m - characteristic of the solid material; S_m – possible maximum solids concentration; h_{cr} - dimensionless thickness of high-concentrated bottom layer of solids in critical regime; ψ_o - ration of suspension viscosity to conveying liquid viscosity at the top of pipe; α and β_* - known correctives of solids influence on the maximal velocity at the kinematic flow axis.

Numerous comparisons of the calculation methods developed in Krill (1990) and Bounarski et al.(1996) with the available experiments for a broad class of disperse materials showed rather good agreement between theoretical and experimental data (Sobota et al, 1996). Because of entire lack of experimental data in the bibliography for studied dense material it is difficult to assess the reliability of calculating the parameters for such materials. Therefore, we tried to compile the bibliography data of the known heavy particulates and our experimental results as a basis for compilation. As an example, Figures 1 and 2 show the hydrodynamic characteristics of slurry with iron ore concentrate (ρ_s = 4630 *kg/m^3*, d_s = 0.031 mm) in the pipe of D = 103 mm (Berman et al., 1984).



a)

b)

Fig.1 – a) pressure gradient *I* vs. slurry velocity, and b) critical velocity V_{cr} and pressure gradient *I* vs. average volume concentration *S*
(iron ore concentrate, ρ_s = 4 630 kg/m^3, d_s = 0.031 mm, *D* = 103 mm)

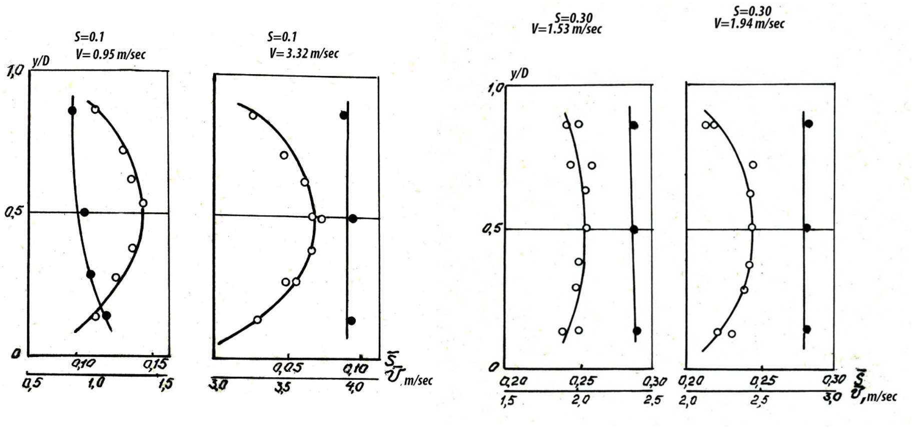
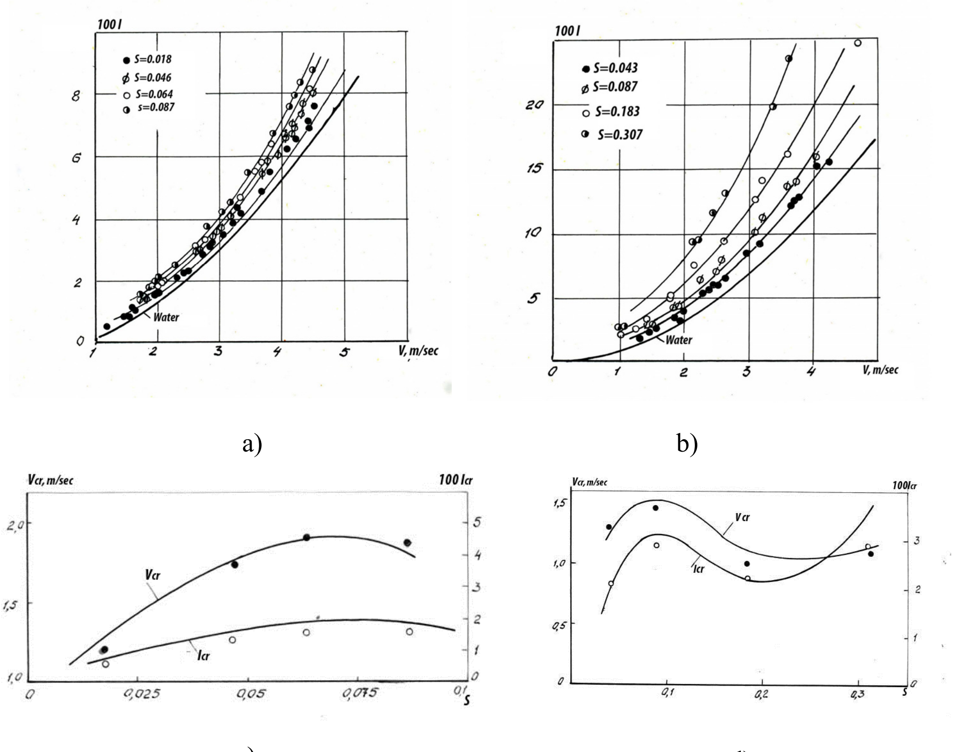


Fig.2 Vertical concentration (●) and velocity (o) distribution
(iron ore concentrate, ρ_s= 4 630 kg/m^3, d_s = 0.031 mm, *D* = 103 mm)

Based on these experiments, a preliminary conclusion that dynamic and kinematic characteristics of such materials are in essence similar to that of the lighter materials, such as sand, coal, tailings etc., can be made. Also as seen from the above, the characteristics of such suspensions at medium concentrations *S* > 0.3 may slightly differ from the properties of conventional (Newtonian) suspensions.



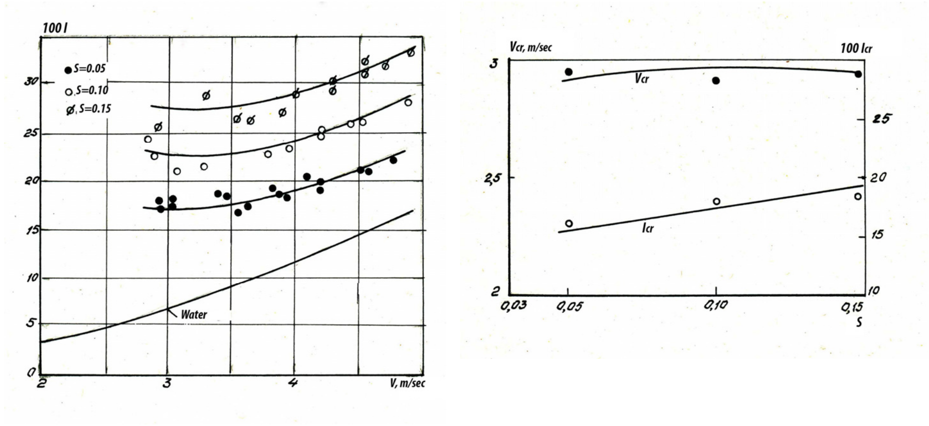
a) b)

c) d)

Fig.3 – a) – b) pressure gradient *I* vs. slurry velocity, and c) – d) critical velocity V_{cr} and pressure gradient I_{cr} vs. average volume concentration *S*. Points – experimental data, curves – calculation according suggested method, Kril and Berman (2000); (iron ore concentrate, $\rho_s = 4\,450$ kg/m^3, $d_s = 0.058$ mm; a), c) – $D = 206$ mm, b), d) – $D = 103$ mm)

The comparison between suggested calculation method (Kril and Berman, 2000) and the experimental data of different dense solid materials with $\rho_s > 4000$ kg/m^3 is certainly of great interest. Figures 3 and 4 show such comparison for iron ore concentrate (ρ_s = 4450 kg/m^3), and fire scale (ρ_s = 5370 kg/m^3). There is documented a fairly good agreement between calculated and experimental data in a wide range of conditions.

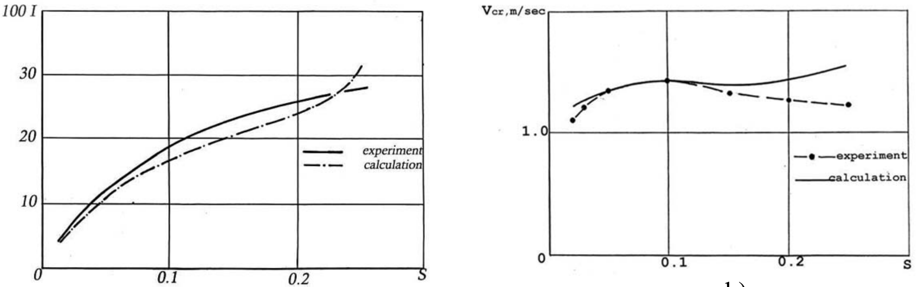
Let us now turn to a basically new problem - hydrotransport of super dense materials. As far as we know there is no information on the subject in the literature. Due to practical activity demands we conducted a study of the main parameters of such material hydrotransport. Copper powder of median particle size 42.1 micron and density $\rho_s = 8477.7\ kg / m^3$ was measured on experimental loop of inner mean diameter 25.4 mm to determine basic parameters, i.e.: critical velocity, and hydraulic resistances.



a)

b)

Fig. 4 – a) pressure gradient *I* vs. slurry average velocity *V,* and b) critical velocity V_{cr} and corresponding critical pressure I_{cr} vs. average volume concentration *S,* when slurry moving in the pipeline of $D = 103$ mm. Fire scale of $\rho_s = 5370$ kg / m^3 and $d_s = 1.41$ mm was used as a tested material. Points - experimental values, solid curves - calculation according our method (Kril, 1990)



a)

b)

Fig.5 – a) pressure gradient *I* under critical velocity condition, and b) critical velocity V_{cr} versus concentration *S* (copper powder, $\rho_s = 8\ 477.7$ kg/m^3, $d_s = 4.21\text{x}10^{-5}$ m)

The experiments were carried out in the range of mean flow velocity $V_{cr} \leq V \leq 4$ m/s and average volume concentration $0 \leq S \leq 0.37$. We do not present here all results of the experiments and we focus on comparison of the selected characteristics at critical operation condition with calculation method (Kril and Berman, 2000). The results of this comparison, by analogy with the results considered earlier, are shown in Figure 5, and. verify the reliability of the suggested method to calculate basic parameters of hydrotransportation even previously unknown super heavy dispersed materials.

In future, we expect to conduct similar experiments with even more dense material such as fine-grained tungsten (density $\rho_s = 19000$ kg/m^3). However, based on the obtained results, we may preliminary conclude that the suggested method can be reliably used for prediction of flow behavior of suspensions containing rather dense solids.

3. HIGH-PRESSURE PNEUMOTRANSPORT

Due to aggravated transport problems in present and future, many experts presently discuss an idea of the possibility to use existing gas pipelines for pneumatic transportation of coal and other bulk materials in various gas carriers. The pressure in these systems could measure up to 10 MPa, and this transport was called ‘high-pressure pneumotransport.

To successfully construct such systems, at first a variety of problems should be solved; one of which is developing reliable methods of hydrodynamic calculation allowing defining all the necessary system parameters (e.g. flow rate and operational velocity, pressure, critical velocities, etc.). And the above obtained results, and suggested method, can be useful. From these parameters, one can at the design stage evaluate the principal possibility, promising outlook and reliability of implementation of this transportation technique.

In recent years, scientific basis of pipeline transport has been studied by various institution including the Institute of Hydromechanics of NAS of Ukraine (Berman and Orlova, 1993; Kril and Berman, 1996; Kril and Berman, 2000). Up to date, the numerical algorithms for solving this problem were developed. Thereby it was found that to closure the differential equation system of uneven or unsteady flow of a solid particles-gas mixtures at high pressure, which we set up to simulate the problem, a scientifically grounded method should be developed as a separate sub-program for calculating the basic parameters of gas-solid mixture flow in pipes, ignoring the carrying agent compressibility. When developing these calculation methods, all features of the considered transportation method should be taken into account; and first of all, relatively high pressures in pneumatic systems. In addition, the development of calculation methods is complicated by a total absence of experimental data for such flows, too. All this necessitated an innovative approach to solve this problem.

As it is known, pressurized pneumatic conveyance systems studied here suggest weighted solid particle motion in the gas flow. Such flows are known as particulate-carriers. One of the most common types of them is a pipeline hydrotransport, of which calculation methods are the subject of this paper. It is obvious that features of hydraulic and pneumatic transport are mainly caused by different physical properties (density and viscosity) of the carrying agent. Indeed, if at hydrotransport of a material as coal in the water the relative density equals to about 1.4 - 1.9, then at conventional pneumatic transport this value comes up to 1000 times larger, and at high-pressure pneumatic conveying is about 100 times greater.

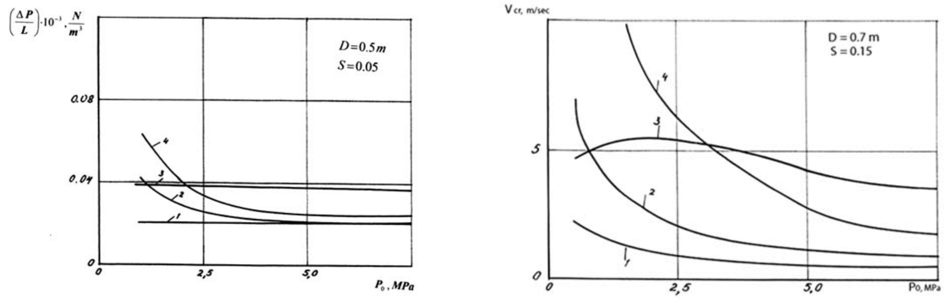
Despite these differences, hydraulic and pneumatic transports have many common: uneven distribution of concentration and velocity of mixture along the flow height. Moreover, this distribution curves are almost identical for hydraulic and pneumatic transports. The curves of pressure gradients and critical velocities have the same similarities. Taking into account that the high pressure pneumatic transport considered here is supposed to use such carriers as natural gas, combustion gases or carbon dioxide, it becomes clear that under such conditions the properties of these carriers will approach the ones of water at hydrotransport.

From the foregoing it can be concluded that there are well-founded prerequisites to extend the already developed and tried out slurry pipeline calculation method to high pressure pneumatic conveying systems. For these systems, a number of unknown initial parameters entering to the basic calculated characteristics were determined from special auxiliary experiments.

At the same time, to issue final recommendations for calculation of the pneumotransport parameters ignoring the carrier compressibility it is necessary to verify validity and reliability of these characteristics. As follows from our survey (Kril and Berman, 1996), a sufficient number of experimental material and relevant empirical dependences in the field of pneumotransport of various disperse materials are available. At that, these data are highly limited in respect of the experiment pressures which usually did not exceed 0.5 – 1.0 MPa.

In principle, as an option, one could compare the experimental data with the proposed calculation methods. We chose a slightly different approach: for a given specific particulate material, the values calculated according to the most well-known in the literature methods were compared with those ones obtained by means of our calculation. To be specific, fine coal was selected as a transported material ($\rho_s = 1500$ kg/m^3 and $d_s = 0.85 \cdot 10^{-4}$ m).

As an example, the results of this comparison are shown in Figure 6.



a) **b)**

Fig.6 – a) pressure gradient under critical velocity condition, and b) critical velocity of pneumotransport V_{cr} on initial operational pressure P_o.
a) – 1 – calculation according to Solov'yev [11]; 2 – calculation according to method of Univ. of West. Australia [4]; 3 – calculation according our method; 4 – calculation according to Smoldyrev [9];
b) – 1 – calculation according to Saks [8]; 2 – calculation according to Solov'yev [11]; 3 – calculation according our method; 4 – calculation according to Smoldyrev [9]

4. CONCLUDING REMARKS

As can be seen from this figure, a comparison of the proposed calculation method fairly well matches the known methods of hydraulic resistances (Figure 6a) and critical velocity (Figure 6b) calculations at normal pressures.

Given the fact that the proposed calculation algorithm works quite well for the case under normal pneumatic pressure (Figure 6), as well as for the traditional hydraulic transport (Figures 2, 3, 4, and 5) one could assume that the suggested method is relatively comprehensive. We can therefore expect that an "intermediate" (between conventional pneumatic and hydraulic transports) region of “high-pressure pneumotransport”, we are interested in, can be at the first approximation calculated according to the above proposed algorithm.

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