

EXPERIMENTAL AND THEORETICAL RESULTS OF PIPELINE SLURRY TRANSPORT IN BULGARIAN MINING INDUSTRY

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A brief history and analysis of Bulgarian slurry pipeline transport practice in the mining industry is presented. The basic intention of this paper has been devoted to the development of generalized methods of hydraulic calculation of such slurry pipelines. Some results of laboratory experiments of hydraulic losses of Bulgarian pyrite solid-water concentrate transported in horizontal pipes are presented. The previously developed method for calculation of the main parameters of hydraulic transport of solids particles, based on kinematic structure, especially the concentration and velocity distribution in the slurry flow, was summarized and tested, and compared with experimental data of hydraulic losses. It can be considered as a basis for hydraulic design and implementation of industrial and main pipelines for various purposes.

KEY WORDS: pipeline hydrotransport, pressure gradient, critical velocity

1. INTRODUCTION

A recent mining exploration of Bulgarian areas with ore deposits shows a relatively good perspective of the mining activity in the country, and quite investments are provided by Bulgarian and foreign companies. Rhodopes mountain, Srednogorie and territories around the town of Trun are the prospects for continued development. There are several ore enrichment plants in the country and tailings are conveyed to respective tailing ponds by pipelines. One of the first slurry pipeline hydrotransport system in Bulgaria was designed and built about 45 years ago near the town of Kardzhali. Then such systems are built and operated at different sites in the country, and some have been decommissioned. Hydraulic studies for the hydrotransport of fine-grained solids to satisfy the engineering practice were carried out in Bulgarian Academy of Sciences and some engineering institutes. Nowadays, to meet the emerging needs, designing and building of new systems is forthcoming. There is need of optimization of the hydraulic pipeline systems and their hydraulic operation.

2. A BRIEF HISTORY AND CURRENT STATE OF MINING IN BULGARIAN TERRITORY

Mining in the Rhodope Mountains in Bulgaria has been known ever since prehistoric times. The hypothesis that more than 7 millennia ago the Balkans were the home of a primal metallurgical culture, which emerged from the region and spread the craft of mining and smithing to Europe and Asia, has its advocates among influential Bulgarian and foreign scientists and researchers, Sabev & Yordanov (2014). Mining in the Rhodope region witnessed a new surge during Roman times (I-IV century A.D.) due to the increased demand for metals.

A detailed study of the geology of Eastern Rhodopes was conducted in the period 1926 - 1935 with the help of German geologists and several concessions for the extraction of lead and zinc ores were reserved. Mining received a significant boost in the period 1948 – 1955, thanks to the Soviet specialists working together with Bulgarian geologists and chemists. A joint Bulgarian-Soviet enterprise – GORUBSO (“Gornorudnoe Bolgaro-Sovetskoe Obshtestvo”) - was founded in May 1950. The extent of mining in the years of socialism led to a rapid demographic and social development process in the Rhodope Mountains, but proved unsustainable. In the 1960s Bulgaria became eighth in the world in terms of extraction of lead, and twelfth with regard to zinc. After 1989 mining in the Rhodopes was affected by the Bulgarian transition to democracy and market economy in virtual governmental chaos, and by the fact, that in the early 1990s metal prices on world markets decreased sharply.

Currently there are four ore enrichment plants operating in the Rhodopes: in Laki, Kardzhali, Roudozem and the village of Erma Reka. Tailings are conveyed to respective tailing ponds by pipelines. For example, the 3500 m pipeline hydrotransport system of Kardzhali was designed in 1973, steel 300 mm pipes for transport of about 110 l/sec. The metal concentrate derived there is transported for processing to a metallurgical non-ferrous-metal factory KCM near town of Plovdiv. Currently, this is the only operational metallurgical plant on the Balkans. In terms of ensuring resources, the companies conduct explorations for new ore deposits in and around existing mines.

Industrial Cluster “Srednogorie Med” integrates Bulgarian companies which define the industrial character of the area of Central Srednogorie of Sredna Gora and the Balkan Mountains - basic industries of mining and processing of copper, gold-containing ores and copper concentrate and high-tech companies, Srednogorie (2011). Ore processing is performed in a dressing mill by grinding, flotation, thickening and filtration. The waste from the enrichment is stored in tailing “Chelopech” as part of tailings used to fill the seized areas in the mine.

The Assarel mine and Assarel concentrator plant for copper concentrate recovery are two of the major production workshops of the Assarel-Medet JSC Mining and Processing Complex, which is the largest Bulgarian mining company for open pit mining and copper ore processing, Figure 1. The tailing pond has been operating since 1989. Pipeline hydrotransport is used for the removal of the waste. The tailings pulp has specific gravity of 2.74 t/m³ with a discharge of about 1000 l/sec, Abadjiev & Trishanov (1991).

The first studies on the exploitation of gold in the municipality of Trun in the territory of Western Bulgaria were developed in 1939 and “Zlata” mine was opened in the 1970’s.



Figure 1. A view of the „Assarel Medet“, the largest open pit mine on the Balkans.

According to a new plan 8 gold and silver mines will be opened in the territory, three of which will be open pit mines, MiningSee (2017). The construction of two tailing ponds and ore processing plant are also foreseen. However, because of environmental issues it is still questionable whether the plan will come true.

3. EXPERIMENTAL RESULTS

Special laboratory experiments have been done for measurement of hydraulic resistances of pipe flow of a typical Bulgarian pyrite concentrate, Ivaniv, Hrebec&Chara (1991), having following parameters: solid density $\rho_s=4400 \text{ kg/m}^3$, average-weight particle diameter $d_s=0.0483 \text{ mm}$, $d_{50}=0.0275 \text{ mm}$, and $d_{85}=0.06 \text{ mm}$, and particle size distribution on Table 1.

Table 1

Particle size distribution of Assarel pyrite concentrate.

class $d_i \text{ [mm]}$	yield	$P_i \text{ [%]}$ summary	$d_{cp,i}$	$d_{cp,i} P_i$
-0.4 +0.2	0.61	100.00	0.3	0.183
-0.2 +0.16	3.31	99.39	0.18	0.5958
-0.16 +0.125	3.62	96.08	0.1425	0.51585
-0.125 +0.08	6.18	92.46	0.1025	0.63345
-0.08 +0.04	30.14	86.28	0.06	1.8084
-0.04 +0.025	18.51	56.14	0.0325	0.60158
-0.025 +0.01	25.12	37.63	0.0175	0.4396
-0.01 +0.007	1.88	12.51	0.0085	0.01598
-0.007+0.0045	2.45	10.63	0.00575	0.01409
-0.0045	8.18	8.18	0.00225	0.0184
	$\Sigma = 100.00$			$\Sigma = 4.82615$

Experimental tests were done on 3 different pipe diameters with increasing slurry volume concentration S from 0.006, 0.149, up to 0.345. Experimental pressure gradient versus V curves are shown on Figure 2.

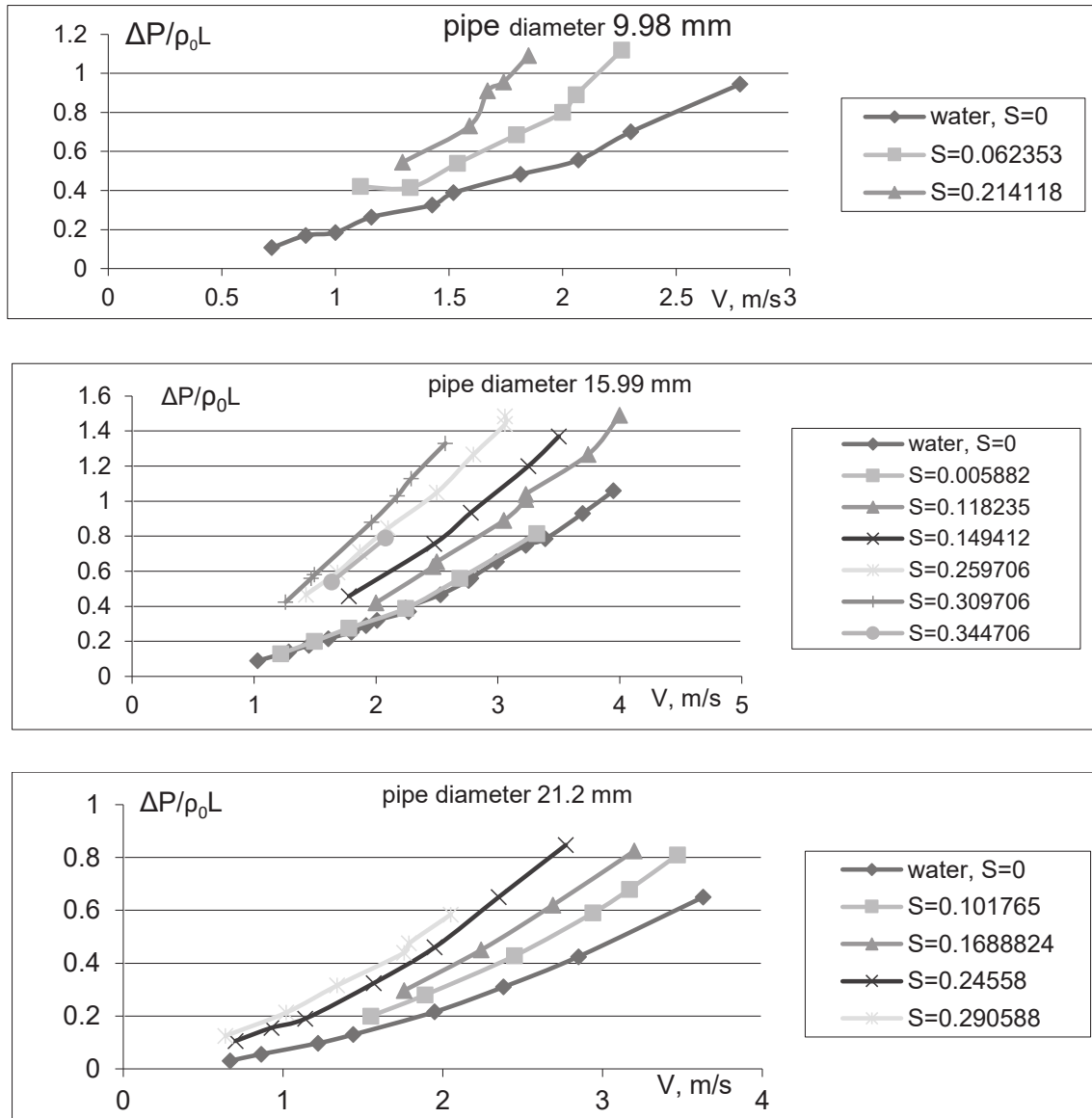


Figure 2. Results of experimental measurements of hydraulic resistance in three pipe diameters $D=9.98$ mm, $D=15.99$ mm and $D=21.2$ mm, Ivaniv, Hrebec&Chara (1991).

S - averaged volumetric solid concentration.

Let us now turn directly to discuss one of the more important problems in the area of calculation, design and operation of the mentioned above hydraulic pipeline systems. This problem is related to the development of a hydraulic method for calculation the hydrottransport of suspensions in pipes. Availability of this calculation method allows to supply a stable work of all transport system and step up a reliability and durability of hydraulic pipelines and all hydraulic equipment.

4. METHODS OF CALCULATION

As is known, for designing hydrotransportation systems the hydraulic resistances and critical velocities as the basic parameters needed to be determined. These parameters are closely related to the flow kinematic structure, so their calculation, strictly speaking, is not possible without accounting the fields of averaged concentrations and velocities in the slurry flow. In this regard, to develop a science-based methodology for calculating the parameters of pipeline transportation of disperse materials, the following main theoretic problems must first be solved: to determine the distribution laws for suspended matter concentration and for flow averaged velocities over the pipe cross section and to deduce the master curves of hydraulic resistances and transportation critical velocities versus parameters defining them. We solved the problem of the distribution of disperse matter concentration and of slurry flow averaged velocities for the hydrotransport systems based on heterogeneous two-phase flow equations recorded within the framework of the discrete concept, Kril (1990), Berman et al (2015). To this, one can add that unknown initial parameters entering to these relationships were determined from special auxiliary experiments. Thus found formulas for distribution of concentration and averaged velocities, Kril (1990), Berman et al (2015), were successfully used when calculating hydraulic resistances and critical velocities of hydrotransportation of different dispersion materials.

These structural dependencies for calculating the pressure gradient I and the critical velocity V_{cr} of hydro transportation according to Berman et al (2015) can be represented as:

$$I = \frac{\rho_0}{\rho} \frac{\lambda}{(1-a)\omega^2} \frac{V^2}{2gD} + (\Delta_s - 1) S \frac{W_s}{V} (1-S)^n \varphi \quad (1)$$

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

where

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

The notation in (1) - (3) are as follow : ρ_0 - averaged suspension density at the top of pipeline; ρ - density of conveying liquid; λ - hydraulic resistance factor; a and ω - parameters of degree of axial asymmetry of the velocity field; n - semi-empirical coefficient (function of Reynolds number for solid particles); V - averaged velocity of flow; g - acceleration due to gravity; D - internal pipeline diameter; Δ_s - ratio of solids

density ρ_s to density ρ ; W_s - mean weight settling velocity of solids; S - averaged volumetric concentration of solids in the flow; φ - parameter of non-uniformity of concentration distribution along flow depth; D_* - reduced pipe diameter ; $D_* = 0.1m$; $Re_* = V_f D_* / \nu$ - the Reynolds number with ν - kinematic viscosity of conveying liquid; k_0 - solids friction factor; σ - rate of reduction of k_0 in the presence of powdered fraction in solid particles; S_m - utmost possible solid concentration in the flow; h_{cr} - dimensionless thickness of high-concentrated bottom layer of solids in critical regime; ψ_0 - 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 method developed in Kril (1990), Berman et all (2015), Bournaski, Berman&Kril (1996), with the available experiments for a broad class of disperse materials showed rather good agreement between theoretical and experimental data. In Figures 3 and 4, as an example, are presented the comparison of calculations and experimental data for materials we are interested - different kind of tailings.

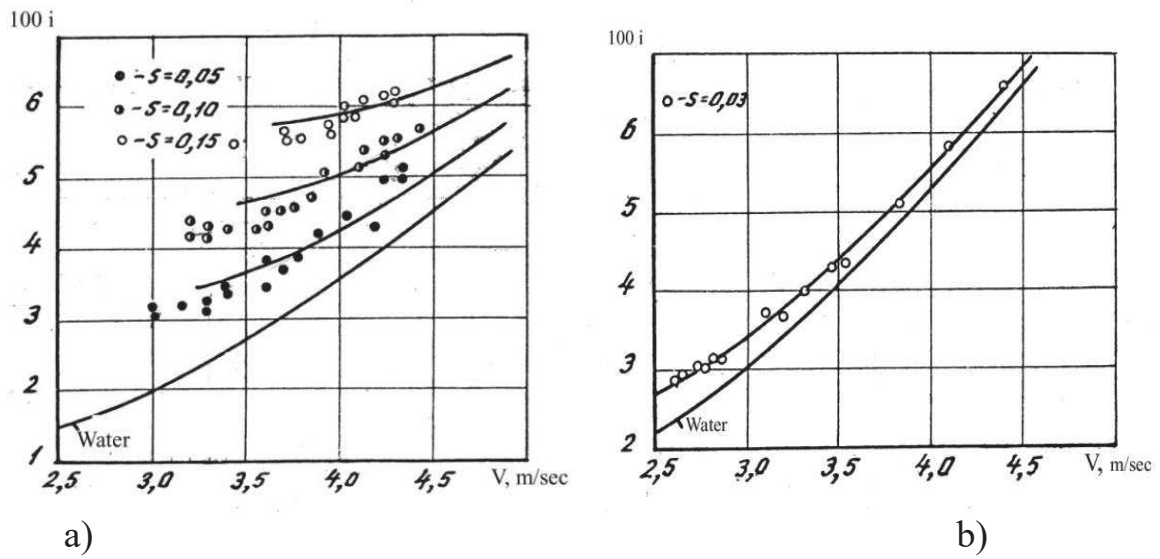


Figure 3. Specific friction head $100i$ vs. slurry average velocity V and average volume concentration S . Tailings with $\rho_s = 2980 \text{ kg/m}^3$, a) $d_s = 0.52 \text{ mm}$, $D = 307 \text{ mm}$; b) $d_s = 0.21 \text{ mm}$, $D = 206 \text{ mm}$; Points - experimental values. Solid curves - calculation according our method.

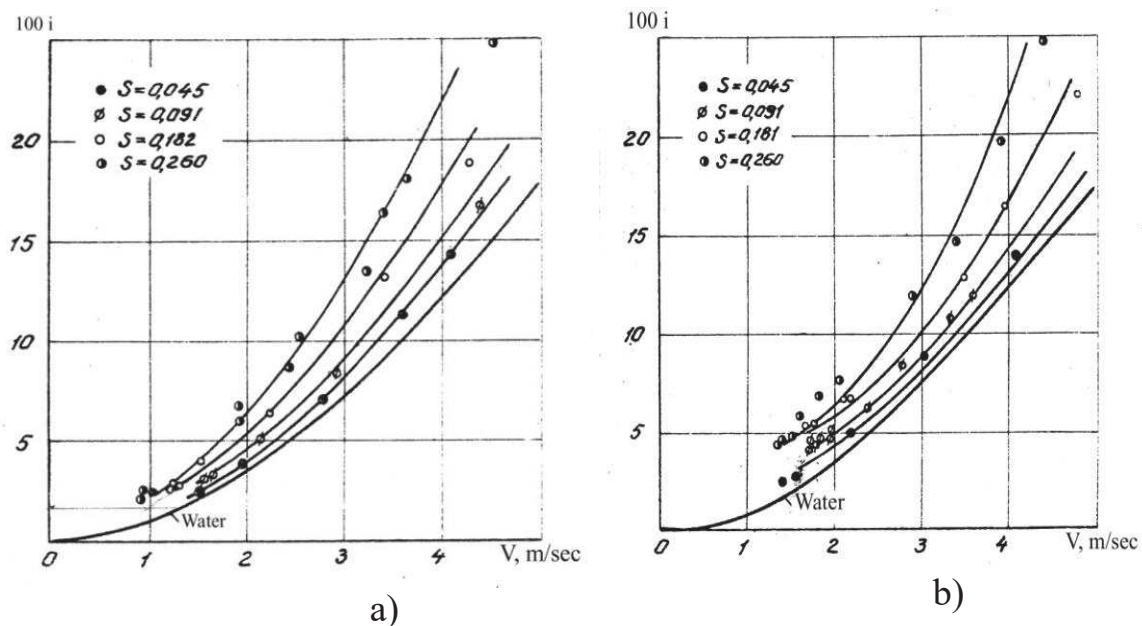


Figure 4. Specific friction head $100i$ vs slurry average velocity V and volume concentration S . Tailings with $\rho_s = 3200 \text{ kg/m}^3$, a) - $d_s = 0.071$ mm, $D = 103$ mm; b) - $d_s = 0.15$ mm, $D = 103$ mm; Points - experimental values. Solid curves - calculation according our method.

In Figures 5, the comparison of calculations and our experimental data for Assarel pyrite concentrate are presented. For definiteness, the biggest diameter of the experimental pipeline $D = 21.2$ mm was chosen.

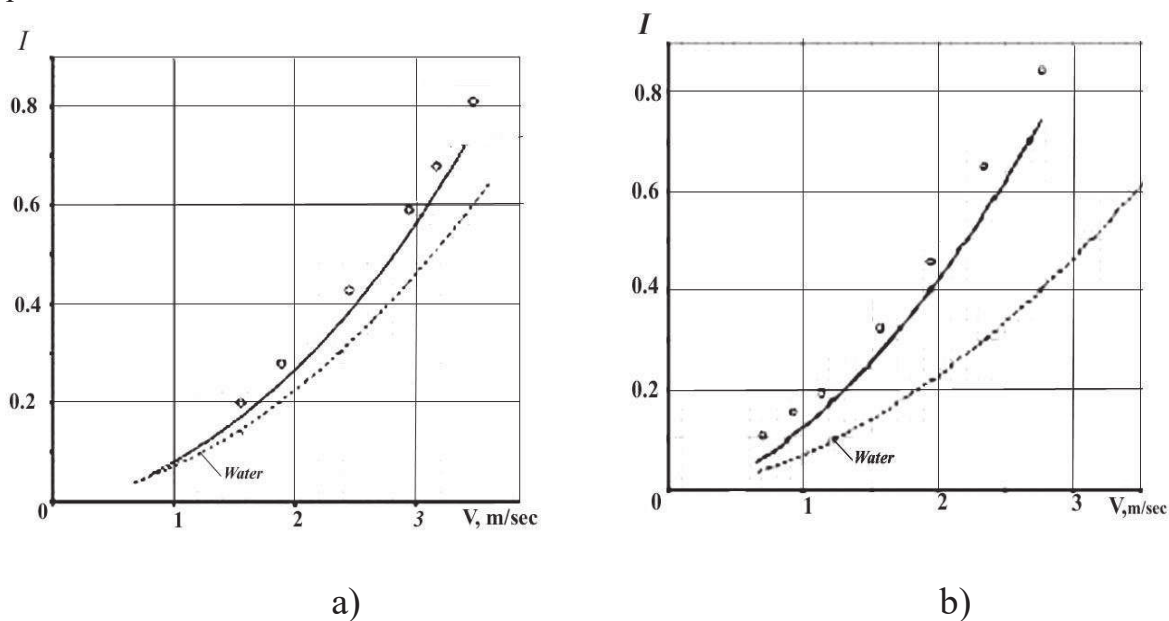


Figure 5. Pressure gradient I vs. slurry velocity V and volume concentration S . Assarel pyrite concentrate, $\rho_s = 4400 \text{ kg/m}^3$, $d_s = 0.0483$ mm; $D = 21.2$ mm. a) - $S = 0.102$, b) - $S = 0.246$. Points - experimental data, curves - calculation

As can be seen from these quite good correlations between theoretical and experimental data (Figures 3, 4 and 5), presented calculation algorithm (1)-(3) maybe used as a base for designing of industrial transportation pipeline systems for tailings and another kinds of solid dispersion materials.

5. CONCLUDING REMARKS

In conclusion it should be noted that the general information concerning hydrotransport systems presented in this paper, the specific results of experimental studies of pipeline slurry flow of Bulgarian mining materials and the proposed numerical algothrohs can be considered as a base for calculation, optimization and appropriate selection of all hydromechanical equipment for design and implementation of industrial and main pipelines for various purposes.

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