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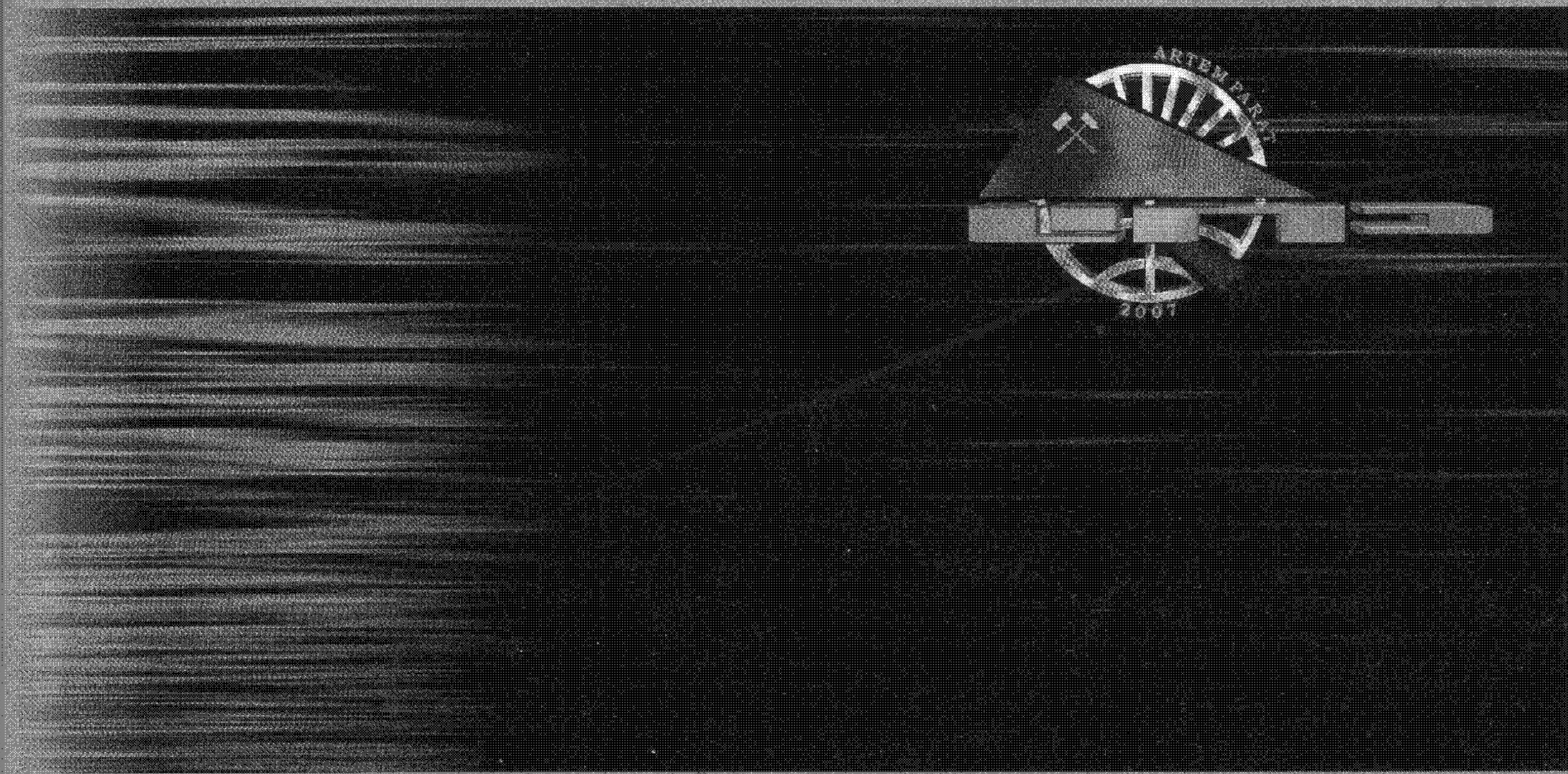

School of Underground Mining

TECHNICAL AND GEOINFORMATIONAL SYSTEMS in MINING

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Technical and Geoinformational Systems in Mining

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Advanced method for calculation of deep-water airlifts and the special software development

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ABSTRACT: The advanced method for calculation of deep-water airlifts is developed. It completely takes into consideration the specifics of solid material transportation through the water and air mixtures flow in the airlifts lifting pipe. The special Exact Calculation software which implements the method was developed. The impact of the structural and discharge parameters onto the energy capacity of the hydraulic lifting process is defined using the software as well as their efficient values for the basic version of the experimental facility at the deposits development depth equals to 6000 m.

Over the past few decades the world community is growing the interest in the development of mineral deposits of the World Ocean. Ocean floor hosts polymetallic ores whose resource is much more than similar land based one. Nowadays, the most challenging in terms of industrial development are deposits of polymetallic nodules, polymetallic sulfide ores, cobalt-manganese crusts, hydrates and phosphorites (Kirichenko 1989). The leading companies of the U.S., UK, Canada and Germany are working on the development of technical tools and methods for extracting ores from the ocean floor. Intensive work in this direction is also being conducted by the National Oceanographic Institute in India, joint-stock corporation of development a deep-ocean resources (DORD) in Japan; Research Institute for Exploitation of the Sea in France, a joint organization Interoceanmetal (Bulgaria, Cuba, Poland, Russian Federation, Slovakia and the Czech Republic); Yuzhmorgeologiya in the Russian Federation, the Union for the Exploration and Development of Ocean Mineral Resources (UEDOMR) in China, the Government of the Republic of Korea.

According to the experts, nowadays the most perspective way of transportation of extracted minerals to basic watercraft is deep-water airlift hydraulic lifting (DWA) due to high reliability in challenging conditions of deep water. Along with this DWA has a significant energy capacity, so the trend of development is the improving the facility efficiency. One of the ways to improve the efficiency of hydraulic hoisting is a selection of their rational design and discharge parameters that minimize energy consumption during transportation.

This article is devoted to solving the actual issue of grounding of the rational design and discharge parameters which provide the hydraulic hoisting exploitation with the highest technical and economic indicators.

Obviously, the accuracy of determining the DWA rational parameters directly depends of the accuracy of the used calculation method.

The analysis of the known methods for DWA calculation has shown that existing methods based on the using of the dimensionless flow rate characteristics and on integrating of the differential equations of motion of the mixture with the various complexity require further improvement. The methods do not take into account the specifics of facilities exploitation, especially transportation of solid material in the composition of the multiphase flow, as well as have many nondescript empirical coefficients. In addition, a common disadvantage of all existing methods is the lack of proper experimental verification. Therefore, the issue of development of the most accurate calculation method and as a consequence, the determining of rational values of design and discharge parameters of deep-water hydraulic hoisting remains open.

The **aim** of this article is the development of an advanced method for the DWA parameters calculation and the special software, as well as establishing the patterns of influence of the design and discharge parameters of hydraulic hoisting to energy capacity of transportation processes.

Existing methods for calculation of deep-water hydraulic hoisting can be divided into two groups. The first group includes methods based on homogeneous models (Kirichenko 2001; Grabow 1977; Grabow 1978, Ueki Syro 1979; Weber 1982) of multicomponent flows and the "energy" interpretation of the occurring processes (the balance between the available and supplied power). Available power – is hydraulic power required for transportation of the pulp, and supplied power – power of supplied air flow. The first group includes Grabow method (Grabow 1977 & Grabow 1978) and Ueki Siro method (Ueki Syro 1979) based on significant assumptions which simplify the mathematical apparatus. However this simplification negatively affects the results accuracy. The advantage of these methods is the calculation speed which allows to calculate a large number of options for establishing a qualitative influence of various factors on the efficiency of hydraulic hoisting.

The second group includes Polyarsky (Polyarsky 1982) and Chaziteodorou (Chaziteodorou 1972) methods, based on the "forced" interpretation of the processes and forces momentum conservation equations separately for each phase. This ultimately adds up to a separate model (Kirichenko 2009) of multiphase flow. Methods of the first group underestimate the required air flow for a given solids based facility capacity, and thus overstate the efficiency value. The main reason for this discrepancy is the fundamental difference between the methods of both groups while determining the total pressure gradient. The calculations performed in a wide range of baseline data shown negligible discrepancy between the results (less than 4...6%) while determining the friction loss using the methods of both groups.

Pressure loss to overcome the weight of the slurry column is not the case. The first group methods assume that these losses, for example at the bottom of the airlift pipe, are the ones required for the lifting of the pulp in the water. However, according to the Polyarsky and Chaziteodorou methods the losses to overcome the weight of the slurry column are the pressure losses based on lifting of solid particulates only in the water.

When solid material densities equal to $\rho_1 = 1100...1400\ \mathrm{kg/m^3}$ and solid phase concentration equals to $C_1 = 0.03...0.12$ pressure loss to overcome the weight of the slurry column calculated by the methods of the second group exceeds the corresponding loss calculated by the methods of the first group by 60...70%. Obviously, this significant discrepancy affects the pressure in the mixer a lot and as a result, the value of required air flow.

Chaziteodorou method is briefly described above (Chaziteodorou 1972). The method is based on the separate flow model of multiphase flow, where the three-phase flow is considered as a superposition of two-phase flows: water-air mixture and pulp. The essence of the method is solving of equation system which consists of three continuity equations and the three motion equations for each phase, supplemented by a trailing dependencies and boundary conditions.

The pressure and specific gravity of air, velocity of the phases and cross-sectional areas occupied by each phase as a function of the coordinates of the pipeline are determined as the result of the solution of this system. The initial value of the specific gravity of air depends on the pressure in the mixer. The method of successive approximations is used to find the value of the pressure and compressed air flow in the mixer the way that the pressure in the upper section of pipe equals to the atmospheric pressure while solving equations of motion in the lifting pipe. Required initial values of velocities and areas of the phases are determined by solving of a system of two continuity equations and two motion equations for the pulp in the feed tube. This system is obtained by zeroing of an air phase in the equations which describes the three-phase flow in a lifting pipe. Methods of the second group are more reasonable and accurate than the methods of the first group (see Figure 1), mainly due to basing on a universal separate models of multiphase flow, taking into account the effect of interfacial forces. Nevertheless, it has a number of disadvantages, mostly related to incorrect interpretation of certain physical processes and the neglect of several factors which significantly affect the efficiency of transportation.

For example, the assumption that solid particles in three-phase mixture are transported by fluid only does not reflect the physics of the formation of airlift "traction", which ultimately affects the calculated speed of solids lifting. It is also mistakenly assumed that the drag coefficient of the pipeline remains constant along the entire length of the lifting pipe and does not depend on the specific structure of the flow. In addition, the bottleneck of the method is the lack of sustainable transportation of solid particles control while fluctuations of speed and much more.

The authors believe that the improving of the calculation method accuracy associated with the requirement of the complete accounting of all main factors which determine the physics of the solid particles transportation processes. Based on years of experience in the industry, the authors identify the following key factors and mechanisms:

1) Transportation of solid particles in the lifting pipe of deep-water hydraulic hoisting is performed by air/water mixture but not water. I.e., the basic flow characteristics are determined by the similarity criteria, depending on the parameters of the mixture rather than a liquid.

2) The drag coefficient of the lifting pipe is not constant along the length of the pipeline and depends of the basic parameters of the flow, expressed in terms of characteristics of the mixture and above

all the specific flow structure. Each flow structure corresponds to a different mathematical model. The dependencies for determining the drag coefficient for different mixture flow structures are given in (Kirichenko 2009). The expressions for determining of the boundaries of flow structures in the lifting pipe of deep-water hydraulic hoisting depending on the defining criteria of the flow are also presented in that article. As a result of adaptation of these characteristics to the base hydraulic hoisting from a depth of 6000 m, we have firstly obtained the following values of the stability limits of mixture flow structures, expressed by the discharging gas content variation range β.

- the boundary between bubble and slug structures $\beta = 0.25...0.3$;
- the boundary between slug and annular structures $\beta = 0.65...0.8$;
- the boundary between the annular and dispersed structures $\beta = 0.92...0.94$;

3) The condition for sustainable transportation of solid particles, according to which transportation flow rate must exceed the critical speed up to 15...20% (Adamov 1982) should be considered at each step of integration of the motion equations along the airlift pipeline. The following formula (Adamov 1982 & Skorynin 1984) is used to determine the critical speed of the pulp in the feed tube taking into account the cojoint fall of particles group:

$$V_{cr.p} = \left(1-0.35C_{vol}\right)\left(1-\left(\frac{d_n^a}{D_p}\right)^2\right)\times$$

$$\times\left(1-C\right)^2\left(\frac{4\cdot g\cdot\left(d_n^a\right)^2\left(\rho_1-\rho_0\right)}{3C_x\cdot\rho_0}\right)^{0.5}, \qquad (1)$$

where C – throttling concentration of solids in the pulp; C_x – drag coefficient of solid particle and water; ρ_0 – fluid density, ρ_1 – solid material density; C_{vol} – volumetric consistency of the slurry in the inlet pipe; d_n^a – average diameter of the nodules; D_p – pipeline diameter; g – acceleration of gravity.

The following dependence is used accordingly for the airlift lifting pipe (Adamov 1982 & Skorynin 1984):

$$V_{cr.m} = \left(1-0.42C_{vol.m}\right)\left(1-\left(\frac{d_n^a}{D_p}\right)^2\right)\times$$

$$\times\left(\frac{4\cdot g\cdot d_n^a}{3C_{xm}}\left(\frac{\rho_1}{\rho_m}\left(1+q_z\right)-1\right)\right), \qquad (2)$$

where $V_{cr.m}$ – three-phase mixture critical speed in the lifting pipe of deep-water hydraulic hoisting; $C_{vol.m}$ – mixture volume consistency in the lifting pipe; q_z – the average specific air consumption; C_{xm} – drag coefficient of solid particles in the mixture; ρ_m – mixture density.

The presence of a downward phase of the solid particles movement in gas shells in the slug flow structure should be additionally taken into account. The slug flow structure is the most dangerous possibility of failure (crisis) of sustainable solids transportation. This may cause the backing of the pipeline (Kirichenko, Evteev & Romaniukov 2007).

4) It is necessary to correct design scheme of the method by adjusting the discharge parameters to guaranteeing the required transportation velocity in cases of solids sustainable transportation breaches.

5) The opportunity of sound "locking" in the lifting pipe (critical flow) which limits the effectiveness of hydraulic hoisting (Kirichenko 1989) as well as the possibility of "flooding" of the flow at the annular and dispersed flow pattern mixture (Walys 1972) should be taken into consideration.

6) The air solubility and the transportation pipeline angle influence to the value of the real volumetric gas content (Kirichenko & Sdvizhkova 1990, Kirichenko, Samusia, Avrahov & Ivanchenko 1991) must be provided.

7) The impact of the supplying air system characteristics (compressor station + air line) to the operational modes of the facility (Kirichenko, Avrahov & Samusia 1989) must be taken into account.

Considering these factors an advanced method for calculating the hydraulic hoisting (AMCHH) which improves the accuracy of the results has been developed by authors.

The laboratory experiment (Samusia, Evteev & Kirichenko 2008) has been performed in order to approve AMCHH. Experimental investigations have been conducted in the hydraulics and hydraulic drive laboratory of the Mining Mechanics Department of the National Mining University. The experiment was based on an integrated experimental hydraulic stand that allows to perform the physical modeling of one-, two-and three-component flows in the pump, airlift and airlift pumping facilities (Samusia & Evteev & Kirichenko 2008). Moreover, the hydraulic stand design provides the variation possibility of the mixer relative dynamic immersion value in the lifting pipe at the ranges equal to

0.4...0.95. This allows to simulate processes of the short mining facilities and deep-water facilities with considerable length.

The calculated values obtained by different methods (adapted for the liquid lifting) and experimental data comparison results are shown on Figure 1.

The chart shows that the Polyarsky and Chaziteodorou methods which use heterogeneous models give more accurate results than the Grabow and Ueki Siro methods, based on a homogenous model. However, the most accurate calculation method is AMCHH developed by authors, which has been chosen as a base one for further investigations.

The comparison of calculated data and experimental data of different researches carried out within the marine and mining conditions was performed for the purpose of bringing the scale of experimental facilities to full-scale mining-sea airlifts. In particular, the Donetsk Polytechnic Institute in conjunction with the "VNIIProzoloto" institute have tested the marine airlift systems for lifting water in the Baltic Sea near the port of Liepaja. Experimental researches were conducted on the basis of the research vessel "Shelf-1" at the depths up to 90 meters (Adamov 1982).

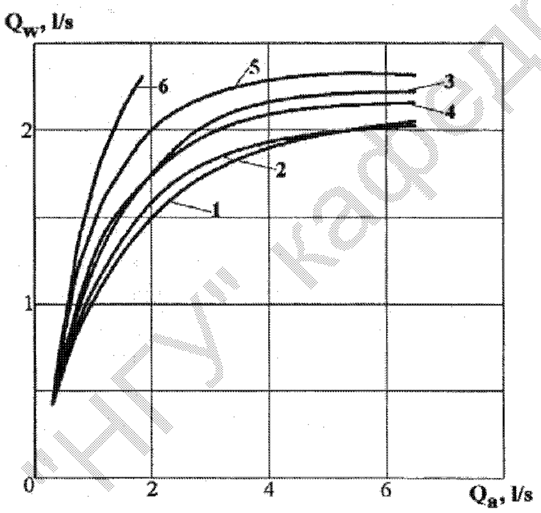

Figure 1. Water volume-flow (Q_w) air volume-flow (Q_a) variation relation under standard conditions; 1 – own experimental data; 2 – AMCHH; 3 – Chaziteodorou method; 4 – Polyarsky method; 5 – Grabow method; 6 – Ueki Syro method.

Figure 2 shows the comparison of experimental data (solid line) and calculated using the AMCHH data (dotted line) for the specified parameters of facility:

1 – $d = 0.1$ m, $L = 5.0$ m, $h = 47.0$ m
2 – $d = 0.15$ m, $L = 8.5$ m, $h = 47.0$ m
3 – $d = 0.1$ m, $L = 0.5$ m, $h = 59.3$ m
4 – $d = 0.1$ m, $L = 21.0$ m, $h = 59.3$ m

where d – diameter of the pipeline; L – length of the inlet pipe; h – mixer penetration.

As follows from the graphs the calculation accuracy increases in proportion to airflow. The maximum accuracy does not exceed 20%.

Researchers from the "Karlsruhe" University (Germany) performed the experimental investigation on the recovery of lignite, sand and gravel using the airlift method (Weber 1976, Weber 1982) in the laboratory and the existing quarry facilities.

The diameter and the length of the pipeline in laboratory facility were equal to 0.1 m and 7.8 m correspondingly. At air flow equals to 0.027 m^3 / s the maximum flow for the solids at this facility were equal to 3.45 kg / s, and the solids volume concentrations in the flow tube reaches the 33% (Weber 1976).

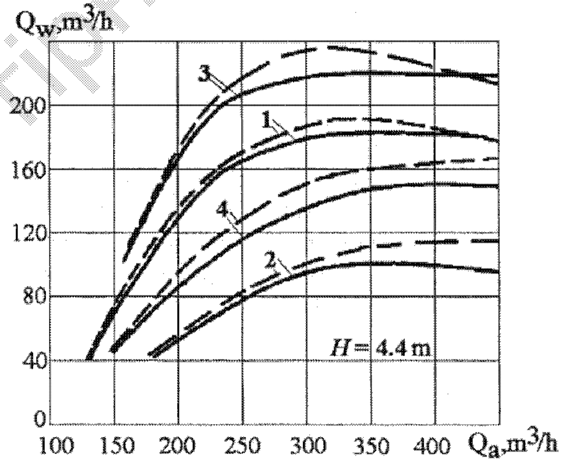

Figure 2. Experimental and calculated throttling characteristic of the marine airlift system comparison.

The airlift system (Weber 1982) with the total length of 441 m has been tested in the "Rheinische joint-stock company" lignite quarry.

The following characteristics of the facility were used: diameter of the pipe 300 mm; mixer penetration 42...248 m, the air volume flow 0.22...0.713 m^3 / s; solid material maximum flow 115 t / h, solid material obtained concentration 0...8%. Experimental investigations were conducted using the short supplying tube ($L_n = 5...6$ m) as well as long one ($L_n = 101...341$ m).

Table 1 selectively shows the experimental data and the air flow values Q_{ac}, which were calculated for the parameters listed in the table using the AMCHH. The maximum discrepancy of these experimental and calculated data does not exceed 24%.

In order to implement the proposed method the "Exact Calculation" software was developed by the authors. It is the C++ console application compatible with win32/64 platforms. The software expects the input data as an XML file and outputs the results in XML format. In addition, the results can be exported to Microsoft Excel (xls) spreadsheet.

Systematic numerical investigations for the basic variant of deep-water hydraulic hoisting (capacity equals to 100000 tons / year for "dry" raw material extracted from the depth of 6000 m) were conducted in order to establish the regularities of design and output parameters of hydraulic hoisting influence on energy capacity of the transportation processes.

The main variable parameters have the following ranges: the real volume concentration of solid material $C_1 = 0.02...0.15$; mixer penetration $H_{mp} = 1500...3500$ m; air mass flow $M_2 = 2.5...65$ kg / s; solid material mass flow $M_1 = 5...12$ kg / s.

The most representative results are selectively shown on Figures 3-8.

Table 1. The comparison of calculated data and experimental data.

Lifting material	Design parameters				Discharge parameters					
	h	L_n	H	$\alpha = \frac{h}{h+H}$	Q_{ae}, m³ / s	Volume concentration C_s, %	Solid flow rate Q_s, m³ / s	Water flow rate Q_w, m³ / s	Q_{ac}, m³ / s	δ, %
Gravel $\rho_s = 2575$ kg / m³ $d_n = 5$ mm	171	101	7	0.96	0.187	1.13	0.002	0.177	0.168	10.2
	174	101	7	0.961	0.256	2.29	0.0045	0.191	0.214	16.4
	177	101	7	0.962	0.384	3.39	0.0057	0.162	0.313	18.6
	180	101	7	0.962	0.405	3.95	0.0095	0.232	0.335	17.3
	186	101	7	0.964	0.260	1.89	0.0038	0.195	0.230	11.5
	216	101	7	0.969	0.249	2.17	0.0039	0.175	0.205	17.6
	222	101	6.9	0.97	0.329	3.7	0.0077	0.201	0.288	12.6
	225	101	6.9	0.97	0.240	2.51	0.0041	0.160	0.194	19.3
	69	290	6.6	0.912	0.570	2.06	0.004	0.191	0.490	14.0
	111	290	6.6	0.944	0.374	4.13	0.0056	0.124	0.306	18.1
	152	290	7.7	0.952	0.262	1.49	0.0026	0.169	0.211	19.3
	104	341	6.3	0.943	0.544	3.22	0.0053	0.158	0.475	12.6
	246	197	6.8	0.973	0.510	4.46	0.00935	0.200	0.439	13.9
	246	197	7.3	0.971	0.367	2.58	0.0054	0.205	0.306	16.7
	42	6.2	7.2	0.853	0.575	4.74	0.0127	0.255	0.470	18.2
	42	6.2	7.2	0.853	0.390	2.67	0.0068	0.248	0.324	17.0
	42	6.2	7.2	0.853	0.233	2.69	0.00535	0.193	0.201	13.8
Sand $\rho_s = 2610$ kg / m³ $d_n = 0.6$ mm	245	197	7.4	0.97	0.484	3.86	0.0075	0.186	0.432	10.7
	246	4.9	6.4	0.971	0.252	2.64	0.0055	0.203	0.223	11.5
	248	4.9	8.4	0.97	0.390	7.1	0.127	0.166	0.354	9.3
	248	4.9	8.4	0.97	0.456	6.4	0.0121	0.178	0.401	12.1
	148	101	8.4	0.946	0.488	5.89	0.0107	0.172	0.455	6.7
	148	101	8.9	0.946	0.220	3.25	0.0052	0.154	0.200	9.1
	148	101	8.4	0.946	0.355	6.01	0.0113	0.176	0.327	8.0
Lignite $\rho_s = 1143$ kg / m³ $d_n = 50$ mm	103	341	7	0.936	0.584	6	0.0169	0.263	0.488	16.4
	103	341	7	0.936	0.713	7.5	0.0201	0.249	0.581	18.5
	103	341	7	0.936	0.412	4.8	0.0116	0.232	0.328	20.3
	153	290	6.8	0.957	0.691	8.6	0.0254	0.270	0.535	22.6
	146	296	7.3	0.956	0.527	7.8	0.0211	0.251	0.408	22.5
	245	197	7.4	0.97	0.505	5.4	0.0157	0.274	0.389	23.0
	245	197	7.3	0.97	0.497	4.7	0.0147	0.300	0.383	22.9
	245	197	7.3	0.97	0.388	4.7	0.0127	0.259	0.296	23.8

Figure 3 shows the relationship between discharge parameters and energy parameters of airlift, which provides the required capacity in a fixed position of the mixer. There is an inflection point (extremum) on the curves shown on graph, which indicates the existence of a rational concentration of solid material which corresponds to the minimum air consumption at selected geometric parameters of the facility. As shown on the graph, the maximum value of efficiency corresponds to the minimum values of specific power and air mass flow.

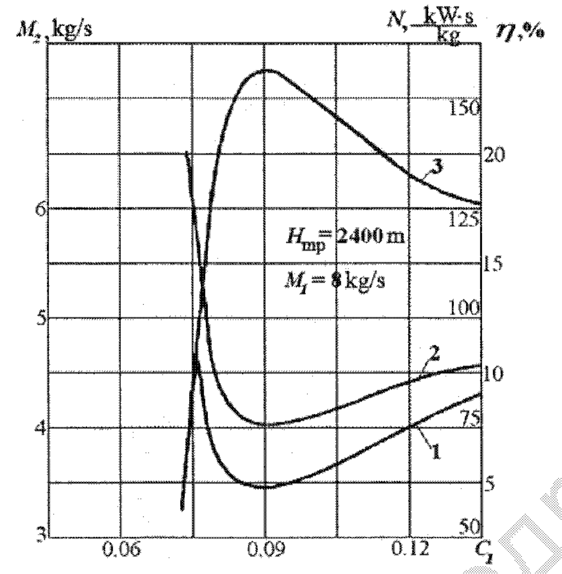

Figure 3. The dependence between the basic parameters of airlift and the real volume concentration of solid phase; 1 – the specific power (N); 2 – airflow (M_2); 3 – Efficiency (η).

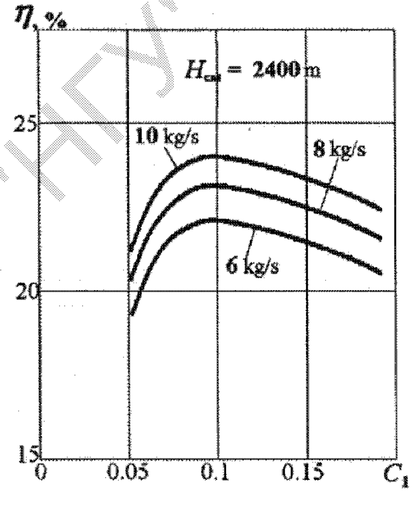

Figure 4. Dependence between the efficiency and the real volume concentration of solid phase for various solids capacities.

Figure 4 shows the influence of the pulp concentration and the capacity of the deep-water solids based hydraulic hoisting to the efficiency of the facility at the fixed mixer penetration.

As follows from the graphs the increasing of the solids mass flow in the investigating range leads to an efficiency increasing. Furthermore each value of the solids capacity corresponds to a rational value of the pulp concentration.

Figure 5 shows the dependence between the air mass flow as well as the airlift efficiency and the real volume of solid phase concentration for a given solids capacity and fixed position of mixer and different pipe diameters.

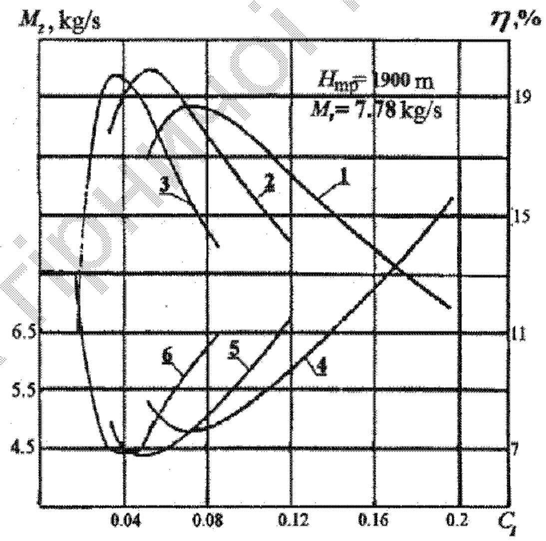

Figure 5. Dependence between the air mass flow as well as the airlift efficiency and the real volume of solid phase concentration at different pipe diameters: 1, 2, 3 – efficiency values for the pipeline diameters equal to 0.20, 0.22, 0.24 m, respectively; 4, 5, 6 – M_2 values for the pipeline diameters equal to 0.20, 0.22, 0.24 m, respectively.

As it is shown on the graphs the maximum efficiency value is achieved with a diameter of pipeline equals to 0.227 m, which nearly coincides with similar calculations for the base version of deep-water hydraulic hoisting provided by VNIPI "Okeanmash".

Figure 6 shows the dependence between the main discharge parameters of the deep-water hydraulic hoisting and the pressure in the mixer at a given solids capacity and fixed mixer penetration for the same pipe diameters. As follows from the graphs decreasing of air flow, providing a given facility capacity at the selected mixer penetration increases the pressure in the mixer as well as the efficiency of the facility.

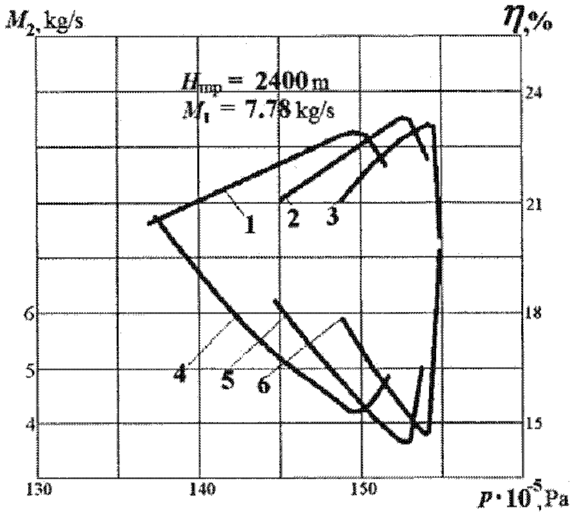

Figure 6. Dependence between the air mass flow as well as the airlift efficiency and the mixer pressure at different pipe diameters. 1, 2, 3 – Efficiency values for the pipeline diameters equal to 0.22, 0.27, 0.32 m, respectively; 4, 5, 6 – M_2 values for the pipeline diameters equal to 0.22, 0.27, 0.32 m, respectively.

As follows from the Figure 7, the minimum air flow rate that provides a given output corresponds to the dimensionless mixer penetration $\overline{H_{mp}} = 0.41$, equivalent to $H_{mp} = 2380$ m. It should be noted that the value of mixer penetration equals to 1900 m has been used in calculations provided by VNIPI "Okeanmash".

Figure 8 shows the dependence between the airlift efficiency and the dimensionless depth of mixer immersion at various solids capacities. As follows from the graphs each capacity of the facility for solids corresponds to the rational mixer penetration which minimizes energy capacity. At the same time in the investigated range of parameters mixer penetration affects the value of airlift efficiency no less (Figure 8) than the diameter of the pipe (Figure 5).

An analysis of the results of systematic numerical experiments established a **new scientific result**. The rational dimensionless mixer immersion of airlift $\overline{H_{mp}}$ which provides the maximum efficiency of facility in the range of airlift solids capacity variation equals to 7...10 kg / s and depths of ferromanganese nodules mining equal to 3500...7000 m is $\overline{H_{mp}} = 0.36...0.42$.

Based on comprehensive analysis and the comparison of the dependences (Figures 3-8) which show the mutual influence of design, discharge and energy parameters of deep-water hydraulic hoisting, for the basic variant of the system, the following rational parameters which minimize power consumption of the facility were determined: $C_1 = 0.09$; $H_{mp} = 2380$ m, $M_2 = 4.12$ kg / s.

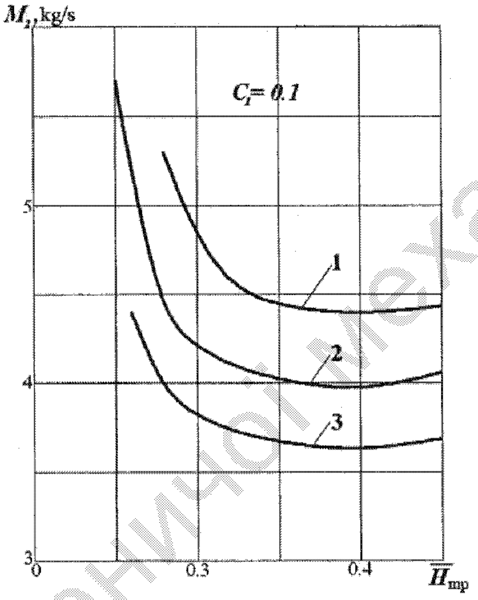

Figure 7. Dependence between the air mass flow and the dimensionless depth of mixer immersion for various solid flow rates; 1, 2, 3 – solid flow rates equal to $M_1 = 10$, 8, 6 kg / s, respectively.

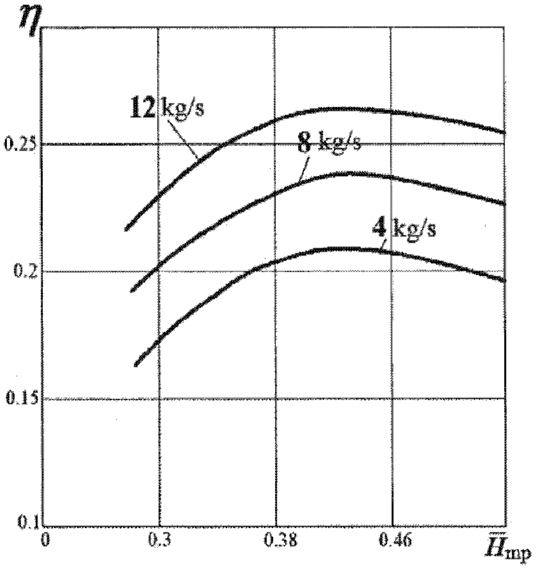

Figure 8. Dependence between the efficiency of airlift and dimensionless mixer penetration for different solid materials flow rates.

The method considered as invention for launching and operating of the DWA with the mixer, which immersion depth exceeds the maximum pressure produced by the compressor has been developed by the authors of article.

The further stage of research is the development of a graphical version of the software, based on cross-platform Qt library, which would visualize the deep airlift processes. There are three variation are planned to be implemented: standalone application, add-in for SolidWorks CAD and the component for the CAE-solution for modeling complex deep-sea mining systems developed by the authors.

CONCLUSIONS

1. The advanced method for calculation of DWA parameters is developed. The method provides highly accurate results due to the consideration of the full facilities operation specifics and features of solid material transportation composed of a heterogeneous mixture.

2. The accuracy of the method is confirmed through own laboratory experiments and comparison with experimental data from other investigations in marine and mining conditions.

3. The "Exact Calculation" application written in C++ for win32/64 platforms has been developed as the software for advanced calculation method.

4. Regularities of influence of design parameters and discharge parameters to the energy capacity of hydraulic lifting processes and their rational values for the basic version of the experimental facility at a depth of 6000 m were determined using the "Exact Calculation" software.

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