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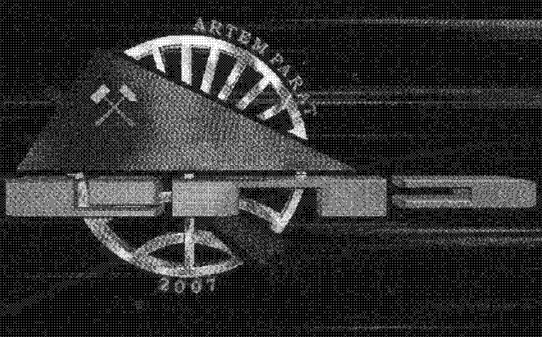

School of Underground Mining

TECHNICAL AND GEOINFORMATIONAL SYSTEMS in MINING

CRC Press
Taylor & Francis Group
A BALKEMA BOOK

2011

PROCEEDINGS OF THE SCHOOL OF UNDERGROUND MINING, DNIPROPETROVS'K/YALTA, UKRAINE, 2-8 OCTOBER 2011

Technical and Geoinformational Systems in Mining

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CRC Press
Taylor & Francis Group
Boca Raton London New York Leiden

CRC Press is an imprint of the
Taylor & Francis Group, an informa business
A BALKEMA BOOK

Technical and Geoinformational Systems in Mining – Pivnyak, Bondarenko & Kovalevs'ka (eds)
© 2011 Taylor & Francis Group, London, ISBN 978-0-415-68877-2

Research of dynamic processes in the deep-water pumping hydrohoists lifting two-phase fluid

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ABSTRACT: A comprehensive methodology for the calculation of dynamics of the two-phase flows has been first developed. The methodology allows studying the whole spectrum of transient processes in the deep-water pump-based installations and provides the precision level needed for this class of problems. On the basis of the developed methodology a special HydroWorks 2p software is developed, allowing to define the parameters of transient processes in the deep-water pumping installations. Using the software it is defined that pressure oscillations and ensuing dynamic stresses often reach critical values, which may pose a risk in terms of efficiency of installation and violation of its integrity.

1 INTRODUCTION

Nowadays in Ukraine there is a shortage of some strategic non-ferrous metals extracted from the continental deposits in traditional way. In this regard, the further growth of mineral resources base in Ukraine is closely linked with the development of ore deposits of the World Ocean.

One of the most promising methods of transportation of solid minerals from the seabed is a pump-based hydrohoist (Fox 1981).

Decision of the of National Security and Defense Council on May 16, 2008 "On measures to ensure Ukraine's development as a maritime state" powered by Presidential Decree № 463/2008 of 20 May 2008, provides for the development of a new "National Programme for research and use of Azov-Black Sea and other regions' of the oceans resources in the years 2009-2034". Thus, development of technical means of lifting minerals from the seabed is one of the priority areas of research. This article focuses on the urgent problem of development of mineral potential of the World Ocean, the solution of which is directly linked to the development of effective methods of regulation and management of deep-water pump-based hydrohoists.

The lifting process of mineral raw materials on a basic watercraft associates with the solution of tasks of calculating the dynamics of two-phase (water and solids) flow, which is due to many transient processes accompanying the work of the pumping unit. Deep-water pumping hydrohoists (DPH) usually operate in non-stationary or quasi-stationary modes because of the long hydraulic paths and specific exploitation characteristics.

The existing methods of calculating the DPH mostly base on the idea of the mixture as a homogeneous fluid (Nigmatulin 1987). The authors of these methods tend to focus on the problems of water hammer giving the solid particles in the flow a passive role which means only increasing the density of the mixture (Kartvelishvili 1979; Makharadze 1986; Wallace 1972; Kyrychenko, Romanyukov, Taturevich 2009). This approach allows using simplified mathematical apparatus, based on the homogeneous model (Wallace 1972; Charny 1975) for calculations, which significantly reduces the accuracy of the results, because water and solid particles have different inertial properties. Obviously, such methods with acceptable for engineering calculations accuracy allow calculating the ground hydrotransport, which can be designed with appropriate safety margin. However, according to the authors of this paper, this approach is hardly acceptable for the calculation of such unique engineering facilities like DPH, because it does not take into account the specifics of marine mining equipment exploitation in difficult conditions of great depths.

The pipeline of DPH is the backbone of the entire subsea equipment. Because of the great length, mass and overall dimensions the pipeline is characterized by dangerous static longitudinal stresses (Kyrychenko 2001). When the carrier vessel moves, the pipeline takes a curved shape experiencing dynamic loads, caused by pitching, as well as various kinds of aerohydroelastic instability of the marine environment (aeolian vibration, galloping, flutter). It is also possible loss of the divergent stability of the pipeline and occurrence of parametric resonance due to interaction with the stationary and pulsating flow of transported fluid. In addition, the processes associated with starting and stopping of pumping units in case of wrong management may be accompanied by the phenomenon of water hammer. These factors will inevitably give rise to additional dynamic stresses that may impair the integrity of the system.

Thus, one of the limiting factors of deep-water hydrohoists development is the lack of effective controlling systems, preventing of the above-mentioned harmful effects. The development of such systems, in turn, is restrained by the lack of research results of unsteady modes and dynamic processes in the deep-water hydrohoists, as well as the mathematical description of the transitional processes and the lack of sufficiently accurate and physically grounded method for calculating the parameters of DPH and its software implementation. The controlling system must be capable of fast "tuning" of the current parameters in conditions of multivariate disturbing influences, which means to possess sufficient efficiency and performance.

Based on the above mentioned features, method of calculation of DPH must meet the following requirements:

– high accuracy due to the lack of safety margin;

– high integrity and efficiency, which means the possibility of studying the entire spectrum of nonstationary and transient processes in frames of a single mathematical apparatus, based on the differential equations of the same type;

Earlier the correct calculation of dynamic processes in hydrotransportation systems, pumping heterogeneous mixtures, was not possible mainly due to lack of adequate, physically grounded mathematical model, which would most fully take into account the specifics of deep-water hydraulics and all range of dynamic effects. Another reason is absence of the law of the speed of sound change in two-phase slurry (Wud 1934).

However, the authors of this paper have managed to obtain such mathematical model of two-phase fluid motion (Goman, Kyrychenko, Kyrychenko, 2008), the characteristic relations for it (Kyrychenko, Shvorak, Kyrychenko, Romanyukov, Taturevich 2011), and the speed of sound change laws (Goman, Kyrychenko, Kyrychenko 2008; Kyrychenko 2009). From now on, the possibility of developing an integrated method of calculating the dynamics of heterogeneous flows has been opened. This method will automatically provide the possibility of calculating the parameters of the full range of dynamic processes in the DPH from slow concentration waves that accompany the processes associated with the launch of the system to fast transients in different emergency situations.

2 FORMULATING THE PROBLEM

The aim of this paper is to develop a method for calculating the dynamics of two-phase flows in the pipelines of deep-water pumping systems for the study of nonstationary and transient processes.

Let us briefly discuss the main components of the methodology. In (Goman, Kyrychenko, Kyrychenko 2008) the flow of liquid and solid particles is reviewed. In the one-dimensional approximation, the equations describing the motion of two-phase flow obtained in (Goman, Kyrychenko, Kyrychenko 2008) look like:

$$(1-C_1)\frac{\partial p}{\partial t}-\rho_0 a_0^2\frac{\partial C_1}{\partial t}+\rho_0 a_0^2(1-C_1)\frac{\partial V_0}{\partial x}=0\,, \qquad (1)$$

$$C_1\frac{\partial p}{\partial t}+\rho_1 a_1^2\frac{\partial C_1}{\partial t}+\rho_1 a_1^2 C_1\frac{\partial V_1}{\partial x}=0\,, \qquad (2)$$

$$\left(1+\frac{C_1 k_1}{2}\right)\frac{\partial V_0}{\partial t}-\frac{C_1 k_1}{2}\frac{\partial V_1}{\partial t}+\frac{(1-C_1)}{\rho_0}\frac{\partial p}{\partial x}=\phi_0\,, \qquad (3)$$

$$\left(\frac{\rho_1}{\rho_0}+\frac{k_1}{2}\right)\frac{\partial V_1}{\partial t}-\left(1+\frac{k_1}{2}\right)\frac{\partial V_0}{\partial t}+\frac{1}{\rho_0}\frac{\partial p}{\partial x}=\phi_1\,, \qquad (4)$$

where

$$\phi_0=-(1-C_1)g\sin\alpha-\frac{\lambda}{2D}\frac{\rho_{mix}}{\rho_0}|V_{mix}|V_{mix}-$$

$$-\frac{3}{8}\left[\frac{C_1 C_{xs}}{R_1}|V_0-V_1|(V_0-V_1)\right],$$

$$\phi_1=-\frac{\rho_1}{\rho_0}g\sin\alpha+\frac{3}{8}\frac{C_{xs}}{R_1}|V_0-V_1|(V_0-V_1),$$

$$\frac{1}{a_1^2}=\frac{\rho_1}{K_1}+\frac{\rho_1}{F}\left(\frac{\partial F}{\partial p}\right),$$

$$\frac{1}{a_0^2}=\frac{1}{a_l^2}+\frac{\rho_0}{F}\left(\frac{\partial F}{\partial p}\right),\ a_l^2=\frac{K_l}{\rho_0},$$

$$K_1=\frac{E_1}{3(1-2\nu_1)},$$

$$\rho_{mix}=\rho_0^*+\rho_1^*=(1-C_1)\rho_0+C_1\rho_1\,,$$

$$V_{mix}=\frac{1}{\rho_{mix}}\left(\rho_0^* V_0+\rho_1^* V_1\right).$$

K_1, E_1, ν_1 – bulk modulus of elasticity, Young modulus and Poisson ratio of solid particles correspondingly; K_l – compression modulus of liquid;

a_l – sound velocity in pure unbounded liquid; R_1 – equivalent radius of solid particles; k_1 – a coefficient, which describes how virtual masses are affected by nonsphericity and concentration of solid particles; g – gravitational acceleration; α – pipeline canting angle; D – pipeline diameter; λ – Darcy coefficient; t – time; C_{xs} – solid particles resistance coefficient; C_i – phase bulk volume; p – pressure; ρ_i – phase real density; $\overset{*}{\rho_i}$ – phase reduced density; V_i – phase velocity; x – longitudinal coordinate; sub-indices mean: "0" –water; "1" – solid particles; "m" – mixture.

It should be noted, that derivative of concentration C_1 enters only into continuity equations (1) and (2). Hence if we expresses the derivative $\dfrac{\partial C_1}{\partial t}$ from equation (2) and substitute it into equation (1), we get general continuity equation:

$$\rho_0 a_0^2 (1-C_1)\frac{\partial V_0}{\partial x} + \rho_0 a_0^2 C_1 \frac{\partial V_1}{\partial x} +$$

$$+\left[(1-C_1) + \frac{\rho_0 a_0^2 C_1}{\rho_1 a_1^2}\right]\frac{\partial p}{\partial t} = 0. \tag{5}$$

Now the set of equations (1)-(4) can be divided into two subsets: first subset includes equations (3)-(5) and contains only V_0, V_1 and p derivatives, while derivative of concentration C_1 is absent. Second subset includes equation (2), contains C_1 time derivative and is connected with the first subset via derivatives of p and V_1. At the same time, first subset is connected with the second one only via concentration C_1 (but not via its derivative). Concentration enters into first subset both as a coefficient and implicitly through ϕ_0 and ϕ_1 variables.

Perturbation velocity in mixture and characteristic relations on the mach front can be derived from the first subset (3)-(5). Equation (2) is in fact an ordinary differential equation for calculating changes of concentration C_1 with time in every fixed point of pipeline (x) assuming that V_0, V_1 and p are already defined as functions of x in every time layer t.

If the transported liquid contains plenty of solid particles (pulp movement), wave movement in the pipeline has some peculiarities, caused by compressibility of solid particles, relative slip between solid and liquid phases (which is present in general case), different inertia of solid substance and transporting liquid etc.

We have to note, that the most complete expression for sound velocity in two-phase mixture D_0 is below:

$$D_0 = \frac{1}{\sqrt{\rho_y\left(\frac{(1-C_1)}{K_0} + \frac{C_1}{K_1} + \frac{1}{F}\frac{\partial F}{\partial p}\right)}}, \tag{6}$$

where

$$\rho_y = \mu \cdot \rho_0\,,\ \mu = \frac{A}{B},$$

$$A = \frac{\rho_1}{\rho_0}\left(1 + \frac{C_1 k_1}{2}\right) + \frac{k_1}{2}(1-C_1),$$

$$B = \frac{\rho_1}{\rho_0}(1-C_1)^2 + (2-C_1)C_1 + \frac{k_1}{2}.$$

Figure 1 shows the dependence of sound velocity on real bulk concentration of solid particles in slurry (hereinafter called slurry buld concentration) for various wave numbers of pipeline and spherical solid particles densities with diameter of 0.005 m. Comparing the depicted curves one can see that behavior of curves has little dependence on density of solid substance.

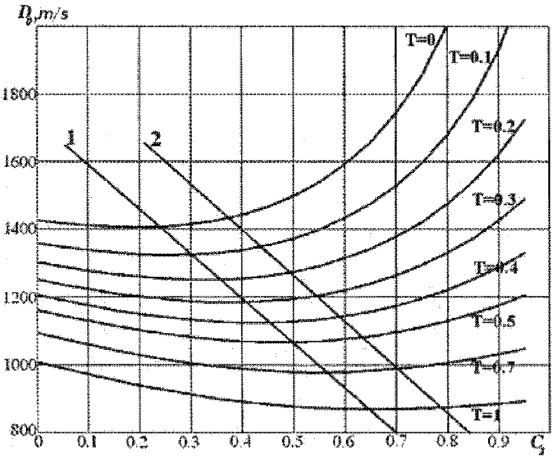

Figure 1. The dependence of perturbation velocity on concentration of solid substance in slurry at various pipeline parameters. ($C_2 = 0$; $\rho_1 = 1600$ kg/m³; $K_1 = 4.5 \cdot 10^{10}$).

Analyzing mentioned relations several conclusions can be drawn. Sound velocity in slurry in general case depends on parameters of both slurry and pipeline. The competing influence of pulp and pipeline parameters defines three specific regions on the plot.

First region is located to the left from line 1 (Figure 1) $D_0 = -2124.7C_1 + 1630$ and corresponds to descending behavior of curves with increasing concentration of solid substance. This happens because increase of solid particles effective volume compressibility is outrunned by growth of pulp density.

The second region is located between the first line and the second line, defined by $D_0 = -2101.8C_1 + 1870$. Second region corresponds to quasi-constant speed velocity at fixed pipeline wave number. In the given range of solid substance concentrations, which is limited by lines 1 and 2, the slurry density is proportional to its volume compressibility. In this region sound velocity depends on pipeline wave number only. Such behavior significantly simplifies calculations, necessary for engineering methodology design. The first approximation of speed velocity is the following:

$$D_0 = -575T + 1415,$$

where $T = \dfrac{K_0 D}{E\delta}$ – pipeline wave number, δ – pipe wall thickness.

Third region is located to the right from line 2 and corresponds to ascending behavior of curves due to overrunning growth of effective volume compressibility of slurry comparing to increase of its density.

From Figure 2 one can conclude that decreasing of solid substance density leads to growth of speed of sound, if other factors are equal.

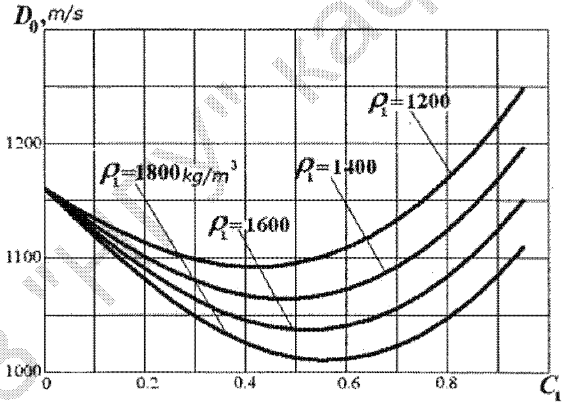

Figure 2. The dependence of sound velocity on solid substance concentration for various values of solid substance density ($C_2 = 0$; $T = 0.5077$; $K_1 = 4.5 \cdot 10^{10}$).

The obtained results lead us to reconsidering of a stereotypic statement, which claims that presence of solid substance in transporting liquid results in growth of sound velocity (Kyrychenko 2009).

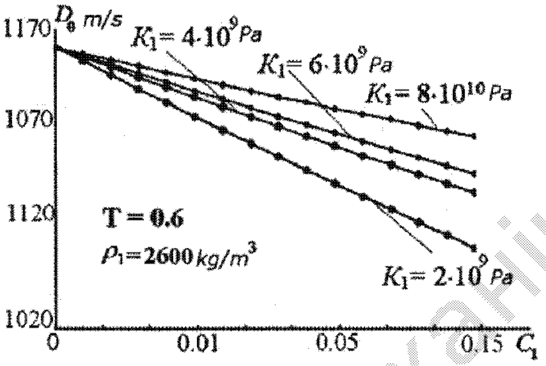

Figure 3. The dependence of sound velocity on solid substance concentration for various values of solid particles volume compressibility ($C_2 = 0$; $T = 0.5077$; $\rho_1 = 1600$ kg/m³).

Speed of sound is also affected by volume compressibility of solid particles K_1 (Figure 3): higher volume compressibility leads to growth of sound velocity, if other factors are equal.

3 CHARACTERISTIC RELATIONS

Paper (Kyrychenko, Shvorak, Kyrychenko, Romanyukov, Taturevich 2011) shows, that for system (1)-(4) characteristic relations are fulfilled on the set of three characteristics:

$$dp + \mu\rho_0 D_0 \left[(1 - C_1)dV_0 + C_1 dV_1\right] - \frac{\mu\rho_0 D_0}{A}\psi dt = 0. \tag{7}$$

$$-dp + \mu\rho_0 D_0 \left[(1 - C_1)dV_0 + C_1 dV_1\right] - \frac{\mu\rho_0 D_0}{A}\psi dt = 0. \tag{8}$$

for following acoustic characteristics

$$\left(\frac{dx}{dt}\right)_1 = D_1 = D_0, \tag{9}$$

$$\left(\frac{dx}{dt}\right)_2 = D_2 = -D_0. \tag{10}$$

and $\left[(1 - C_1)\left(1 + \dfrac{k_1}{2}\right) + 1 + \dfrac{C_1 k_1}{2}\right] dV_0 -$

$$-\left[(1 - C_1)\left(\frac{\rho_1}{\rho_0} + \frac{k_1}{2}\right) + \frac{C_1 k_1}{2}\right] dV_1 - \Omega_1 dt = 0, \tag{11}$$

for characteristics like

$$D = 0, \tag{12}$$

where

$D = x'(t)$ – mach front propagation velocity,

$$\psi = \varphi_l g \sin\alpha - \frac{\lambda \rho_{mix} |V_{mix}| V_{mix}}{2D\rho_0} \varphi_p +$$

$$+ \frac{3}{8}\frac{C_{xs}}{R_1} |V_0 - V_1| (V_0 - V_1) \varphi_1 ,$$

$$\varphi_l = -(1 - C_1)\varphi_p - C_1 \frac{\rho_1}{\rho_0}\left(1 + \frac{k_1}{2}\right),$$

$$\varphi_p = (1 - C_1)\frac{\rho_1}{\rho_0} + C_1 + \frac{k_1}{2},$$

$$\varphi_1 = C_1(1 - C_1)\left(1 - \frac{\rho_1}{\rho_0}\right),$$

$$\Omega_1 = (1 - C_1)\left(\frac{\rho_1}{\rho_0} - 1\right) g \sin\alpha -$$

$$- \frac{\lambda \rho_{mix} |V_{mix}| V_{mix}}{2D_p \rho_0} - \frac{3}{8}\frac{C_{xs}}{R_1} |V_0 - V_1| (V_0 - V_1).$$

It has to be emphasized, that characteristic relations (7), (8) on acoustic characteristics represent relations between total differentials of p, V_0 and V_1 functions along these characteristics, but does not include differential of concentration C_1.

Characteristic condition (11) is fulfilled along $x = const$ lines, so differentials dV_0 and dV_1, which enter the expression, stand for increment of corresponding functions with time at every fixed section of pipeline.

It should be noted, that characteristic relation (11) does not contain differentials of concentration C_1.

Thereby in general case of liquid mixed with solid dispersed phase there are three families of characteristics, and along each of them a specific relation between the total differentials of unknown functions dp, dV_0 and dV_1 is fulfilled.

Concentration differential dC_1 does not enter into these characteristic relations. Concentration C_1 is to be obtained by solving differential equation (2), which is in fact an ordinary differential equation with respect to $\frac{\partial C_1}{\partial t}$. It allows us to use numerical integration using finite-difference schemes.

The obtained characteristic relations can be used as a basis for numerical calculation of non-stationary characteristic of hydromixture using integrated methodology, which represents a combination of characteristics technique for hydrodynamic parameters p, V_0 and V_1 and finite-difference technique for calculating the concentration C_1.

4 METHODOLOGY

Using the above results, let us construct a comprehensive methodology for calculating the dynamics of two-phase flows.

1. Specifying the initial data. In order to calculate the transients in the hydraulic system the following data is used:

– a scheme of hydraulic system (lengths of separate sections and sizes of pipelines; marks of the height of their docking sections; tilting angle of each section; location of major units and valvings of the system (pumps, check valves, gate valves, etc.), system performance, concentration of solid phase and its grain composition, marks of the receiving end output sections of the system);

– data of hydraulic calculation of the stationary mode (flow/pressure characteristics of pumps, their operating points; hydraulic slopes of pipes and pressure distribution throughout the system in stationary mode; operational velocities of components of the slurry; the coefficients of hydraulic and the coefficients of local losses in valvings, etc.

These hydraulic data serves as initial data for calculating non-stationary processes and the phenomena of water hammer in the hydraulic system, resulting from the abrupt change in mode of operation of one or more units or elements of the valve system (de-energizing of the pump or alarm failure, sudden complete or partial overlap of the valves; routine or emergency operation of check valves.

2. Calculation of unsteady hydraulic parameters begins with the partition of the entire pipeline to a finite number of computational elements of a length Δli, the ends of which Ai are reference points for determining the hydrodynamic parameters, and each unit of the hydraulic system is considered as a separate "zero" element, which has zero length, but has its own "input" Ak and "output" Ak +1 (Figure 4).

All the initial parameters of the slurry are determined at all points of Ai at time t0, at which the non-stationary process, which is to be calculated, arises. It is assumed that for each "zero" element (pumps, locking devices and other valvings) hydraulic law of this element (finite or differential equation defining the relationship between differential pressure upstream and downstream of this element and a flow rate of the mixture) is known.

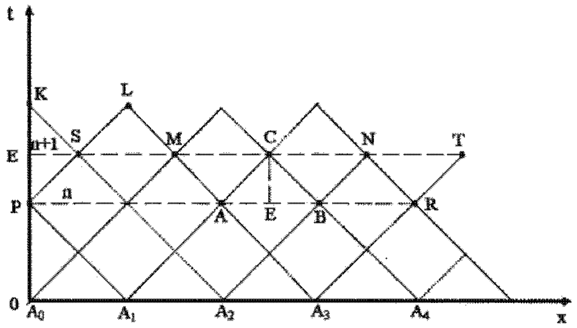

Figure 4. Scheme for using the combined method of characteristics for definition of the unsteady parameters of the slurry.

3. Calculation of unsteady hydraulic parameters goes as follows.

3.1. Determination of the initial distribution of pressure P_0, velocities V_0, V_1 and concentration of the solid particles C_1 in all the nodes $A_i^0\ \left(x_i^0, t=0\right)$

3.2. Coordinates of the points A_i^1 of the new time layer, and new points of observation (x_i^1, t_i^1) are determined from the simultaneous solution of algebraic equations of the characteristics derived from equations (9), (10) by replacing the differentials by finite-difference relations.

$$x - x_A = (D_0)_A (t - t_A), \tag{13}$$

$$x - x_B = -(D_0)_B (t - t_B). \tag{14}$$

The coordinates x_i^1 for all zero elements remain the same. As for the distributed elements, the coordinates of the points of observation x_i^1 vary.

3.3. Calculation of pressure P and velocity of the carrier liquid V_0 and solids V_1 at the new time layer at all internal nodes A_i^1 is carried out by solving algebraic equations

$$p_C - p_A + (a_{00})_A (V_{0C} - V_{0A}) + \\ +(a_{01})_A (V_{1C} - V_{1A}) = (b_0)_A (t_C - t_A), \tag{15}$$

$$-(p_C - p_B) + (a_{00})_B (V_{0C} - V_{0B}) + \\ (a_{01})_B (V_{1C} - V_{1B}) = (b_0)_B (t_C - t_B), \tag{16}$$

$$(a_{10})_E (V_{0C} - V_{0E}) + \\ +(a_{11})_E (V_{1C} - V_{1E}) = (b_1)_E (t_C - t_E), \tag{17}$$

obtained by replacing the differentials by finite-difference relations in the equations of characteristics (7) (8) and (11). Here, the coefficients a_{ij} and b_i are determined by comparing equations (15)-(17) with equations (7), (8) and (11), respectively.

The concentration of solid phase is calculated using equation (2)

$$(C_1)_C = \left[(C_1)_E 1 - \left(\frac{1}{\rho_1 a_1^2} \left(\frac{\partial p}{\partial t} \right)_C + \\ + \left(\frac{\partial V_1}{\partial x} \right)_C \right) (t_C - t_E) \right], \tag{18}$$

where C_{1E} – expressed by interpolating the neighboring nodes A and B, and the derivative $\left(\frac{\partial V_1}{\partial x} \right)_C$ is determined using the values of V at the nodes adjacent to node C, using information from the previous calculation step. The velocity of disturbances propagation (the speed of the shock wave) D is calculated via the formula (6).

3.4. Calculation of hydrodynamic parameters in the boundary nodes (input and output section) as well as "zero" elements is based on the same equations (7), (8), (11) and (18) with appropriate boundary conditions or hydraulic law of each individual element.

3.5. The calculation of each new time layer is carried out by repeating the procedure described in item 3.3-3.4.

5 METHODOLOGY APPROBATION

Numerical experiment. Based on the stated methodology program complex HydroWorks 2p, intended for calculation of dynamics of two-phase flows, is developed. The complex is compatible to CAD-platform SolidWorks 2010/2011 and supports operating systems Windows Vista (x32, x64) and Windows 7 (x32, x64). User is offered two versions of installation package: add-in for SolidWorks and stand-alone application, allowing to work without SolidWorks installed. Application consists of the following units:

– The calculation dll unit, implementing the methodology. The library has an open API interface and can be integrated into other CAD/CAE-systems.

– Dll unit integrated into SolidWorks environment.

– Executable Windows application (.exe).

– Visualizer (dll). Forms reports, displays diagrams and tables.

Among the main functional capabilities, it is possible to select:

– construction of complex parametric pipeline systems;

– complete integration to SolidWorks;

– saving results in external formats (excel, word, txt).

Using the developed software, many numerical experiments have been conducted and the distribution of pressure, velocity and concentration for dynamic tasks in different statements obtained. As an example of the developed methodology usage, we present only the most typical results for the determination of the amplitudes of pressure waves in the pipeline of DPH. One embodiment of such hydrohoist DPH equipped with three electric submersible pumps H1-H3 (Figure 5).

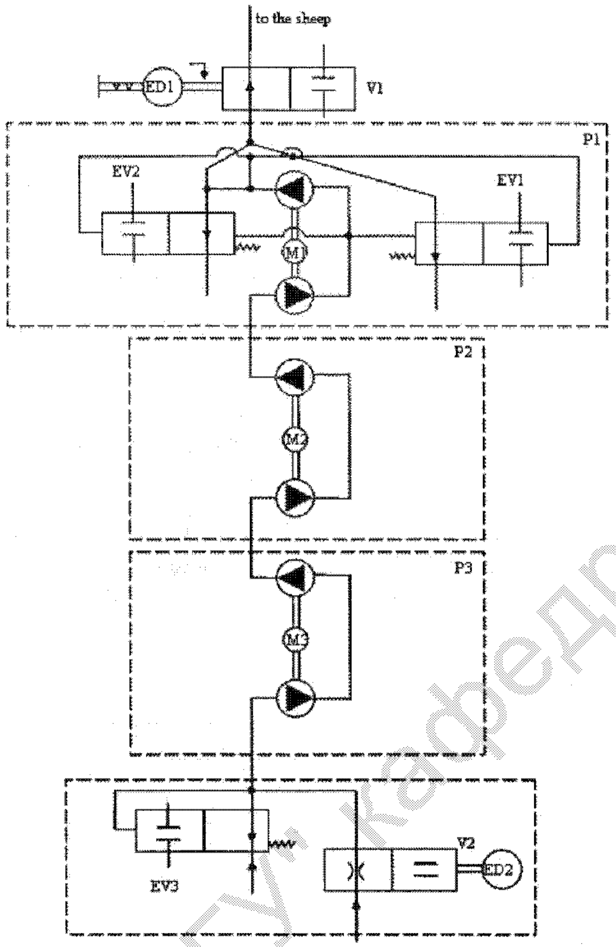

Figure 5. Hydraulic circuit of DPH.

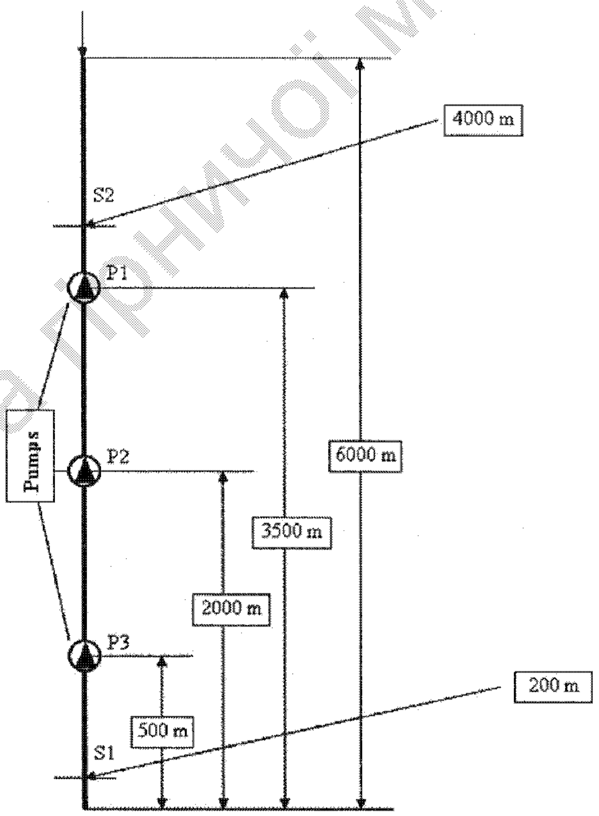

Figure 6. Arrangement of pumping units of DPH.

Slurry submission is conducted from depth of 6000 m. Pumps N1-N3 are installed sequentially in distances of 3500 m, 2000 m and 500 m from a seabottom accordingly (Figure 6) at the closed valves of emergency slurry escape (KAC1-KAC3) and open valves (KШ1, KШ2). Regulation of valves KSH1 and KШ2 is carried out by means of electric drives MSH1 and MШ2. Electric drives of pumping aggregates M1-M3 have possibility of regulation by means of the frequency shifter. It is admitted as well direct switching-on of electric drives in a vessel's network.

Valves of emergency slurry escape KAC1-KAC3 are installed parallel to pipeline.

Let us consider the routine sequential start of pumping units lifting up the water. This launch includes a step-by-step switching-on of the pumps, one after another, with some specified interval of time when filling out a pipeline with a homogeneous liquid.

For the first numerical experiment, step-by-step start-up of pumping units from H3 to H1 has been selected with the 5 seconds interval between launches. Alternative of step-by-step start-up of pumping aggregates is volley start-up when the power is simultaneously applied to all pumps. Research was led taking into account connection of engines of all pumps to the frequency shifters, thus acceleration of shafts of the pumps till the rated speed in both cases happens in 5 seconds.

As control sections for research of dynamic parameters of DPH sections S1 (200 m) and S2 (4000) have been selected.

On Figure 7 diagrams of dependence between pressure of a slurry and time in section S1 are shown at volley and step-by-step start-up of pumping units under the conditions described above.

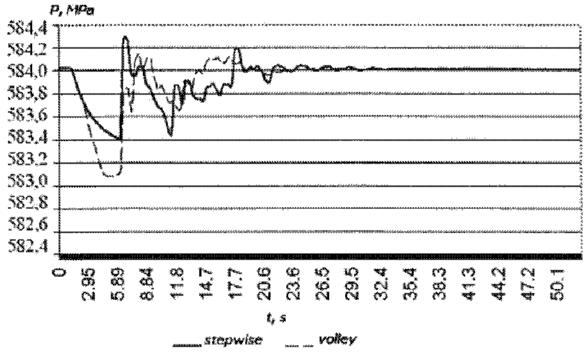

Figure 7. Dependence between pressure (*P*, MPa) and time (*t*, s) at stepwise and volley start of pumping units lifting up water in the section S1.

As seen from Figure 7, the amplitude of pressure fluctuations at step-by-step start of pumping units in the cross section S1 is very different from the same amplitude for the volley launch. The data obtained show that the maximum amplitude of pressure fluctuations for volley launch is observed at the first peak of oscillations and is equal to $9.17 \cdot 10^4$ Pa.

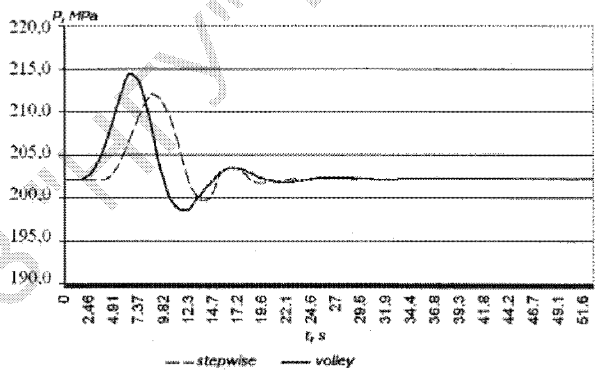

Figure 8. Dependence between pressure (*P*, MPa) and time (*t*, s) at stepwise and volley start-up of pumping aggregates lifting water in section S2.

For sequential start such maximum is much smaller ($6.08 \cdot 10^4$ Pa) and is observed in the first and the third peaks of pressure fluctuations due to the non-simultaneous occurrence of pressure waves in the pipeline and their subsequent superposition. The difference between the maximum deviations from the hydrostatic pressure in the cross section S1 for the volley and step-by-step launches is $3.09 \cdot 10^4$ Pa.

Figure 8 shows the dependence plots between the pressure of the slurry and time in the cross section S2 for the case of stepwise and volley run of the pumps.

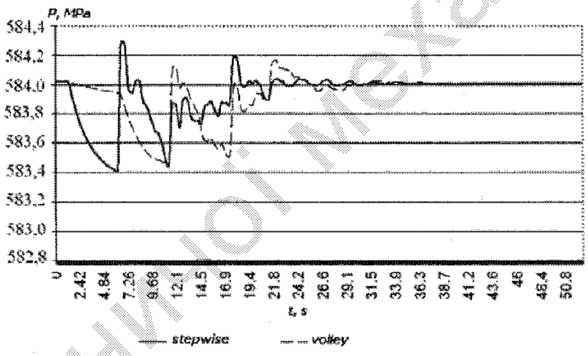

Figure 9. Dependence between pressure (*P*, MPa) and time (*t*, s) at stepwise start-up of pumping aggregates lifting water in section S1 with/without delay

Results of numerical experiment show that the maximum amplitude of pressure fluctuations of slurry for volley launch is observed at the first peak of oscillation and is $21.17 \cdot 10^5$ Pa and at stepwise start – $9.83 \cdot 10^5$ Pa, and also corresponds to the first peak of oscillations. At stepwise start of pumping units, system comes to its stationary mode more mildly, but at such start, it makes sense to delay acceleration time of the first pump's shaft to the rated speed to avoid high load on it at start-up (Figure 9, 10).

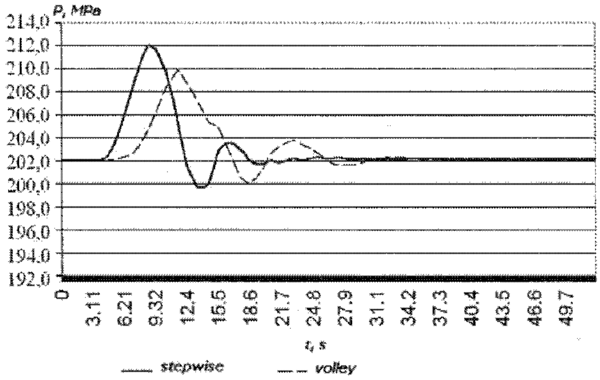

Figure 10. Dependence between pressure (*P*, MPa) and time (*t*, s) at stepwise start-up of pumping aggregates lifting water in section S2 with/without delay.

As seen from the numerical experiments, increasing the acceleration time of the pump has reduced the pressure at the peaks of up to $5.58 \cdot 10^4$ Pa and $7.55 \cdot 10^5$ Pa in sections S1 and S2 respectively.

Of particular interest is the emergency shutdown of the system, when one or more of the pumps breaks down and abruptly closes section of the pipeline by its impeller. Typical feature of this transitional process is that at the time of the stop the pipeline is filled with liquid and solid particles and water hammer occurs in two-phase mixture (Figure 11, 12, 13).

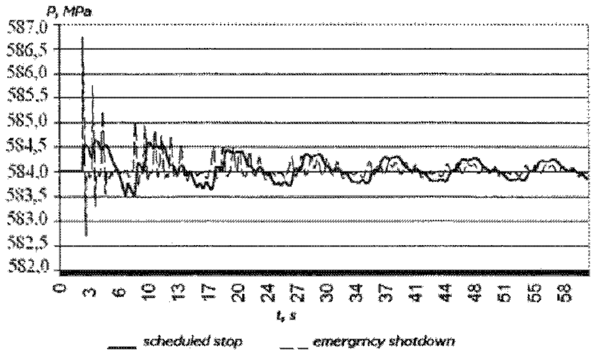

Figure 11. Dependence between pressure (P, MPa) and time (t, s) at an emergency shutdown of pumping units in section S1.

Figure 12 and 13 shows the transients at a scheduled stop of the system starting from the pump unit H1and ending with unit H3, and vice versa with the interval between power off pumps in 20 seconds in cross sections S1 and S3, respectively.

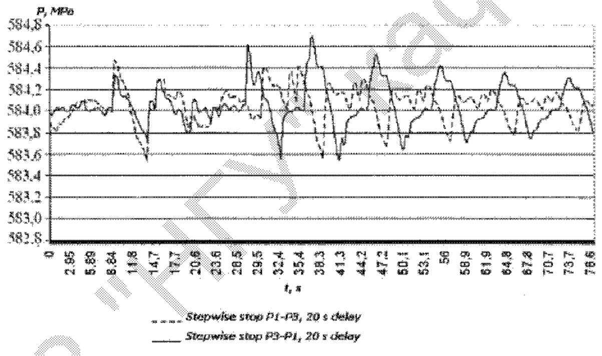

Figure 12. Dependence between pressure (P, MPa) and time (t, s) at a routine stop of pumping units in cross section S1.

In case of an emergency stop of the system, peak values of pressure several times exceed the corresponding values for routine stop. This can cause damage to both pumping units, and the pipeline with poorly predictable consequences. In case of a routine stop, the Figures 12 and 13 show that pressure oscillation amplitude at "bottom-up" algorithm of the pumps' stop is always much lower than the corresponding amplitude at "top down" case, which allows selecting the correct scheme of pumps' shutdown.

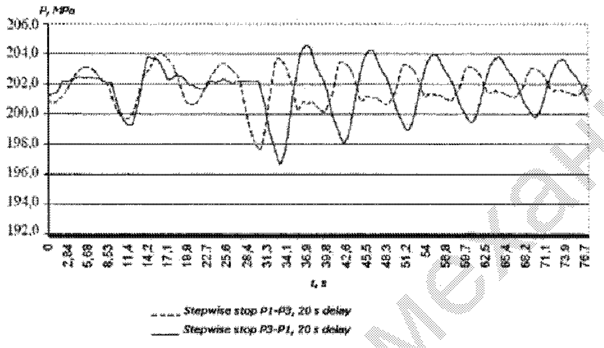

Figure 13. Dependence between pressure (P, MPa) and time (t, s) at a routine stop of pumping units in cross section S2.

Analyzing the obtained results for the three schemes of running the system, can be claimed that the maximum amplitude of pressure oscillation was observed in the case of volley launch of pumping units and reached $21.17 \cdot 10^5$ Pa. This is very unwanted in terms of possible damage to pumping equipment and pipelines in general, and also increases wear and reduces durability of the system elements. The lowest increase in pressure corresponds to step-by-step start-up of the system delaying the launch of the first pump reaching $7.55 \cdot 10^5$ Pa. It is not dangerous and does not create problems in terms of negative effects of water hammer. Such scheme ensures maximum efficiency of start/stop of the system and the risk of damage is minimal due to the avoidance of direct water hammer.

6 CONCLUSIONS

Based on the presented material the following scientific and practical results can be formulated. For the first time a comprehensive methodology of calculating the dynamics of two-phase flows has been developed, allowing quickly and with high accuracy study the full range of stationary and transient processes in the deepwater pumping installations within a single mathematical formalism.

Based on the foregoing, following can be concluded. The investigation of the issue showed that to date there is no method of calculation of nonstationary and transient processes in elements of DPH, taking into account the specifics of their operation in difficult conditions of great depths and providing sufficient accuracy for this class of problems.

Based on the developed methodology, software package HydroWorks 2p is compiled, which allows to solve various problems associated with the two-phase flow and to determine the parameters of non-stationary and transitive modes in the deep-water mining installations. The developed complex is able to calculate the entire spectrum of transients from the launch of the system (pumping only water) up to the processes associated with the regulation and shutdown (operating with slurry).

Using this software package, different transients in deep-water pumping installations have been studied and the basic parameters of the systems depending on the time in different sections of the pipeline are obtained. It is established that the pressure oscillations caused by these dynamic stresses may reach critical values and significantly affect the efficiency of the installation up to the violation of its integrity.

Next stage of work is the use of the developed application HydroWorks 2p for different calculations of deepwater mining installations and making appropriate improvements and extensions to the existing software package.

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