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PARAMETERS OF SYSTEM WITH THE DREDGE HEAD FOR MINING OF FERROMANGANESE NODULES OF THE SEABED

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ABSTRACT

The immediacy of the problem under study is due to the fact that the devices for extraction of solid mineral deposits from the offshore fields are not effective enough and do not meet modern requirements regarding safety, productivity, energy intensity and environmental friendliness nowadays. The purpose of the article is to analyze the influence of hydrostatical pressure, determined by the depth of the capsule location, on the operational and energy characteristics of the proposed mining equipment and the dependence of system performance on the type of a dredge head and its parameters. The leading approach to analyzing this problem was the theoretical study of the processes of hydraulic hoisting and separation of nodules from the bottom, as well as experimental studies of the applied hydraulic motor parameters on the laboratory bench with the processing of results via the mathematical statistics methods and verification of the adequacy of theoretical provisions. As a result, it was found that the energy intensity of the nodule production process depends on the capsule location depth and varies according to the parabolic law; in this case, there is a mode of effective work of the facility to be determined by the model proposed in the article. It was also substantiated that the achievement of the facility performance required level is ensured by the application of a special dredge head, which has an annular channel between the driven hydraulic motor and protective cover, which geometrical dimensions are being determined with consideration for the maximum nodule size and required engine power. It has been experimentally proven that local resistances at the output of the driven hydraulic motor depend on the release coefficient when draining the power fluid into the environment. The materials of the article are of practical value for further studies in the field of determining a high performance technology for extraction of sea-bed solid mineral deposits, as well as during development of technical facilities for the underwater mining of nodules and other solid mineral deposits.

Keywords: hydraulic hoisting, ferro-manganese nodules, intermediate capsule, dredge head, hydraulic drive, deep-sea mining, energy intensity of production.

1. INTRODUCTION

There are huge reserves of Solid Mineral Deposits (SMD), which are of considerable interest to industry at the bottom of the World Ocean. Ferromanganese Nodules (FMN), Cobalt-Manganese Crusts (CMC) and Deep Polymetallic Sulphides (DPS) are the most perspective for development [4, 10].

To date, geological exploration works are being performed most actively, but reliable and effective mechanical appliances with a high rate of productivity are needed for production of deep-sea Mineral Deposits (MD). Two functions of the mining complex can be emphasized when fulfilling SMD underwater mining, i.e: the first one is separation of nodules or crusts from the bottom (extraction) and the second one is transportation of the separated mined rock to the surface (transport) [9]. Separation can be performed mechanically, mechano-hydraulically or hydraulically, and transportation may be mechanical, hydraulic or an air one. Clamshells and dredges [9, 17], scraper-cable units [9, 17, 26], underwater self-propelled vehicles [9, 13, 25, 27, 28] are referred to the mechanisms using a mechanical method for separation and transportation. Suction dredgers [17, 24] are referred to the mechanisms using a mechanical and hydraulical as well as hydraulic method. Hydraulic and air methods are applied in hydraulic dredges [3,5,16] and air-lift dredgers [9, 17, 24]. The above-mentioned facilities do not fully meet the issues of productivity, safety, reliability and environmental friendliness.

The development of SMD underwater production facility, including a surface floating facility, an intermediate capsule with a maintained atmospheric pressure, a benthic mining machine, which includes a dredge head (DH) and a pipeline system (Figure-1) offers the greatest promise [7, 11, 12, 18, 23]. For example, a plant with a self-propelled carriage [13] with a horizontal ripper drum in the form of a working attachment and being driven from an axial turbine can be a bed mining machine [14]. Some problems may arise with reaching a specified productivity in case of applying a dredge head with a horizontal axis of rotation plus with a grab not providing the covering of a destruction zone. It is meant that not the entire nodules separated from the nodule bottom will fall into the pipeline system, i.e. the efficiency coefficient of such a dredge head will be significantly below than one, which leads to loss of performance while producing FMN. Besides, the absence of grab above the destruction zone leads to contamination of a water area. In this paper, we propose to use DH with a vertical axis of rotation with a special grab and being driven from a positive-displacement hydraulic engine in order to compensate for the above-mentioned shortcomings. [18, 20].

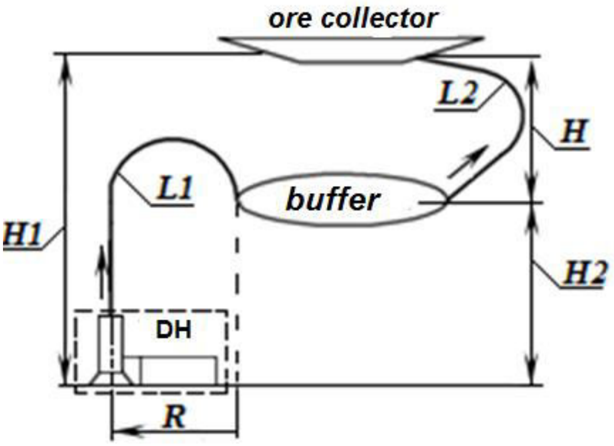

Figure-1. Scheme of deep-water production system.

The issues of modeling a deep seabed mining using the facility with an intermediate capsule were being considered in various studies [1, 2, 8, 29], including the issues of modeling the turbine drive [14, 15] and the hydraulic hoisting of separated nodules through the positive buoyancy sludge pipe to the floating facility hopper-type bin [6, 16]. The issue of the influence of external hydrostatic pressure, determined by the capsule immersion depth, on the production complex operational and energy parameters, remains in abeyance. The question of determining the capsule rational immersion depth is posed as well (H value in Figure-1). Determination of the capsule immersion rational depth will enable to identify the facility effective operation area, which, in turn, will lead to decreasing the process energy consumption and increasing in the efficiency of SMD production.

2. METHODOLOGICAL FOUNDATIONS

FMN production process includes the preparation of nodules for transportation and two-step hydraulic hoisting from the water depth $H1$ up to the sea surface: hoisting from the bottom up to the height of $H2$, carried out due to the used-up hydrostatic head, determined by the capsule immersion depth, and transportation from the capsule to the ore collector at a height of H, produced by dredging pumps installed in the capsule.

When determining the effective regime of system operation, the following parameters were taken as basic: water depth H_1, radius of field treatment *R*, pipeline length L_1 and L_2; pipeline construction connected with the loss of energy, density of solid and sea water $\rho_{тв}$ and ρ_0, hydraulic mix density $\rho_{см}$, specific flow rate q, density of nodules m, volumetric concentration $c_{об}$, flow velocity $v_{см}$, critical velocity of hydraulic mix $v_{кр}$.

The necessary condition at effective operation of the system is the constancy of performance achieved by DH– $G_{тв} = const$.

For sustainable process of nodules hydraulic hoisting from the bottom up to the capsule the condition shall be met:

$$v_{см} \geq 1{,}1 v_{кр}, \tag{1}$$

where $v_{см}$ - average flow velocity; $v_{кр}$ - critical flow velocity. Thus, the necessary and sufficient condition for functioning of the hydraulic hoisting system along the lower section pipeline is the excess of flow velocity critical value determined by the particle size of nodules. The flow velocity at the pipeline bottom is determined as the function of the relative depth of capsule immersion $\overline{H} = \dfrac{H}{H_1}$, taking into consideration pressure losses for the pipeline resistance:

$$v_{см} = \frac{\sqrt{2gH_1}}{\sqrt{L_1}\sqrt{\dfrac{\lambda}{D} + \dfrac{\xi_ш}{l}}} \sqrt{\overline{H}}, \tag{2}$$

where λ - hydraulic resistance factor; $\xi_ш$ - ball joint local resistance factor; D – pipeline inner diameter; l - length of jointed pipeline section with positive floatation, L_1 - length of the pipeline lower section, determined as $L_1 = \sigma H_1 \sqrt{1 + \left(\dfrac{R}{H_1}\right)^2}$ taking into account a radius of treated field circle *R* and the safety factor σ.

Critical flow velocity is determined according to the formula:

$$v_{cr} = 4.9 \frac{\sqrt{gD}}{\sqrt[4]{C}} c_{vol}^{0.36}, \tag{3}$$

where C – drag factor of nodules, S_v - volumetric concentration of hydraulic mix; dimension factor. Volumetric concentration and hydraulic mix density are determined by formulas:

$$c_{vol} = \frac{\rho_{mix} - \rho_0}{\rho_{sol} - \rho_0}, \tag{4}$$

$$\rho_{mix} = \frac{q\rho_0 + \rho_{sol}(1-m)}{q + (1-m)}, \tag{5}$$

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Where $\rho_{тв}$ - density of solid flow component, ρ_0 - water density, q - specific pulp flow rate (ratio of liquid phase volumetric flow rate Q_0 to solid phase volumetric flow rate $Q_{тв}$); m - solid particles porosity. At that solid material volumetric flow rate is the function of DH capacity and, therefore, sea production system $Q_{тв} = \frac{G_m}{\rho_{nd}}$.

The following equation [19] shall be obtained after applying the formulas (2-5) into the formula (1) and performing a number of some simplifications and transformations:

$$z^4 + az^3 - b = 0. \tag{6}$$

$z^2 = \overline{H}$ shall be the only non-negative real root of the equation (6):

$$\overline{H} = \left[\frac{a}{4} - \frac{\sqrt{\dfrac{16a^3N + 9a^4 - 256\left(\dfrac{b}{3M} + \dfrac{a^2}{16} - M\right)^2}{16a^2 - \dfrac{128b}{3M} + 128M}}}{2} + \frac{4a^2 - \dfrac{32b}{3M} + 32M}{32N} \right]^2, \quad (7)$$

where it is designated:

$$M = \left(\sqrt{\frac{a^4b^2}{256} + \frac{b^3}{27}} - \frac{a^2b}{16} \right)^{0,33},$$

$$N = \sqrt{\frac{a^2}{4} - \frac{2b}{3M} + 3M}. \quad (7)$$

Formula (7) determines the relative height of capsule submersion under the water surface, ensuring stable hydraulic hoisting of FMN solid particles of specified particle size from the seabed.

The total energy intensity of production process by the system is composed of the energy intensity of FMN hydraulic hoisting from the capsule up to the ore collector

$$Э_{гп} = \frac{N_н}{\eta_н \eta_э G_m} \tag{8}$$

and depends on the dredging pump power rate $N_н$ and energy intensity of the process of nodules separation from the bottom surface

$$Э_{отд} = \frac{\Sigma N_{по}}{\eta_{мн}\eta_{тр}\eta_{дм2}\eta_{нр}\eta_{эр}G_m},$$

Determined through the required power of the sea-floor equipment and DH in particular $\sum N_{по}$:

$$\Sigma Э = Э_{hl} + Э_{sep} \tag{9}$$

where: G_m – system capacity; $\eta_н$, $\eta_э$, $\eta_{мн}$ - efficiency of the pump, electric motor and oil pump; $\eta_{тр}$ - efficiency of transmission; $\eta_{дм2}$ - efficiency of the drive motor of oil-pumping station (water positive-displacement); $\eta_{нр}$ - efficiency of the feeding water pump, located on the ore collector; $\eta_{эр}$ - efficiency of the electric motor which drives the pump.

Power of the dredging pump will increase with growth of $\overline{H}$. Power of the sea-floor equipment does not depend on the value $\overline{H}$ and is determined by the total motor capacity $\Sigma N_{по}$:

$$\Sigma N_{по} = \frac{N_{эф.дм1}}{\eta_{дм1}} + \frac{N_{эф.пд}}{\eta_{пд}},$$

where $N_{эф.дм1}$ - power expended for sea-floor equipment motor rotation, $\eta_{дм1}$ - efficiency of the oil pump motor; $N_{эф.пд}$ - power expended in the sea-floor motor; $\eta_{пд}$ - efficiency of the sea-floor motor.

Supply of the working fluid (water) to the sea-floor motor is provided by the pump located on the ore collector. Power of the dredging pump installed in the submersible capsule is determined by the following equation:

$$N_н = \rho_{см}\overline{H}H_1\left[1 + \beta\left(\frac{\lambda}{D} + \frac{\xi}{l}\right)\frac{8}{g\pi^2D^4}\left(\frac{G_m}{\rho_{тв}}\right)^2\left(K_4 + K_2K_3\sqrt{\overline{H}}\right)^2 + \frac{0,022}{\left(K_2K_3\sqrt{\overline{H}}\right)^{0,52}}\right] \times$$

$$\times \left[\frac{G_m}{\rho_{тв}}\left(K_4 + K_2K_3\sqrt{\overline{H}}\right)\right] \tag{10}$$

Power of the pump on the ore collector is equal

$$N_{нр} = \rho_0 g H_{нр} Q_{нр}, \tag{11}$$

where $Q_{нр}$ - flow rate of the pump on the ore collector, $H_{нр}$ - head, produced by the pump on the ore collector:

$$H_{нр} = Q_{нр}^2 \left[\left(\lambda \frac{\beta H_1}{D_p} + \sum \xi_p \right) \frac{8}{g\pi^2 D_p^4} + \frac{K^2}{2g\left(2\mu_{o.рас} S\right)^2} \right] + H_{дм2},$$

D_p - diameter of the flexible pipeline, ξ_p - factor of the local resistances along the pipeline length; β - factor of safety; $H_{дм2}$ – used-up in the hydraulic motor head for generation of the drive torque and overcoming hydro-mechanical resistances; K - release factor (taking into account the effect of resistance of the same density receiving environment on the value of head which ejects the water) [22].

Displacement of the exhaust water from oil station drive motor is carried out directly into the water, which determines the additional losses, characterized by the factor K For determination of K value special experiments were carried out. Factor K value was determined as the ratio of flow rate factors when discharge into the atmosphere μ_0 and into the water $\mu_в$ at variable head, i.e.

$$K = \frac{\mu_0}{\mu_в}, \tag{12}$$

where $\mu_0 = \frac{2S}{t_0 s\sqrt{2g}}\left(\sqrt{H-\delta} - \sqrt{H_1 - \delta}\right)$,

$\mu_в = \frac{2S}{t_в s\sqrt{2g}}\left(\sqrt{H-\delta} - \sqrt{H_1 - \delta}\right)$; S - area of the bowl, from which the liquid flew out, s - area of the hole in the jet forming device wedge, H and H_1 - initial and final head, accordingly, t_0 and $t_в$ - time of water flow out in the atmosphere and into the water, accordingly.

In order to ensure the specified level of system capacity, the dredge head of original design is used (Figure-2), which feature the vertical rotation axis, high-torque hydraulic engine of actuator, as well as use of the safety catch, covering the area of face destruction.

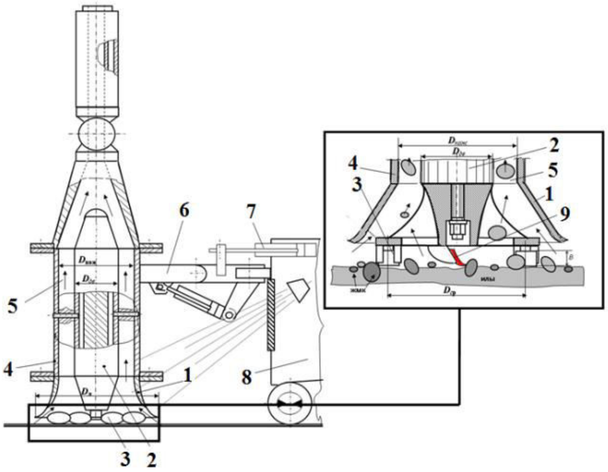

Figure-2. Dredge head for nodules mining:
1 - safety catch, 2 -operating element motor, 3 - operating element, 4 - casing, 5 - ring channel, 6 - boom, 7 - rotary hydraulic engine, 8 - truck, 9 -cutting plates

DH construction (Figure-2) has a vertical axis of rotation of the drive motor 2, which is concentrically mounted in the protective casing 5, which transforms to the safety catch 1, forming the ring transporting channel 5. Such solution allows increasing the efficiency of the dredge head. Nodules, separated with operating element 3, entirely enter the ring channel due to the natural draught $H = H_1 - H_2$ (Figure-1), provided by the presence of submerged capsule with atmospheric pressure. Water flow velocity in the nodules separation zone is less than in the ring channel, therefore, for FMN hoisting from the bottom the following condition must be met:

$$P_{вк} + P_{вв} + P_A > G_к + P_{тр}, \tag{13}$$

where $P_{вк}$ - the force of impact on nodules of ripper inclined plane ($P_{вк} = 0{,}5 S\rho_{тв} v_к^2$); $v_к$ - nodules velocity from the impact on it of inclined at an angle α ripper plane; $P_{вв}$ - lifting force from upward water flow ($P_{вв} = 0{,}5 S\rho_0 v_0^2$); S - cross-section of nodules (midsection); v_0 - water velocity in the FMN ripper zone; P_A - lifting force (Archimedes); $G_к$ – gravity force of nodules of conventionally spherical shape. The difference in the sum of "lifting" forces and "resisting" to the hoisting is equal

$$\Delta P = S\rho_{тв}\frac{\left(\omega R_{ср} tg\alpha\right)^2}{2} - CS\rho_0 \frac{\left(\frac{S_{кк}}{S_{лов}} v_{кк} + \omega R_{ср} tg\alpha\right)^2}{2} + S\rho_0 \frac{\left(\frac{S_{кк}}{S_{лов}} v_{кк}\right)^2}{2} - \left(\rho_{тв} - \rho_0\right) gV, \tag{14}$$

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where ω - angle velocity of the operating element; R_{cp} - radius of operating element tubing adaptor flange; $v_{\kappa\kappa}$ - flow velocity in the ring channel; $S_{лов}$, $S_{\kappa\kappa}$ - area of inlet sections of the safety catch and the ring channel, accordingly; V - volume of nodules.

To control the process of nodules hoisting from the bottom is possible, in particular, through the change in rotation speed of the tubing adaptor flange ω to achieve the effect of nodules entering into the ring channel and provision of dredging head maximum efficiency.

The geometrical dimensions of the ring channel (its inner and outer diameters) shall ensure the passage of specified particle size nodules, and meet the condition of stable hydraulic hoisting, i.e. the velocity in the ring channel must exceed the critical velocity, similar to the condition (1) (18, 21).

$$v_{\phi} = \frac{D_{mp}^2}{4k\delta_{\kappa}\left(D_{\kappa pn} + \delta\right)} \geq 1{,}1 v_{\kappa p}, \tag{15}$$

Where v_{ϕ} - actual flow velocity in the lower pipeline, δ_{κ} - maximum nodules particle size, D_{mp} - pipeline diameter, $D_{\kappa pn}$ - hydraulic engine casing diameter, k - factor of the channel constraint with mounting ribs.

Separation of nodules particles from the bottom surface is performed with the operating element (ripper or cone crown), which rotation is performed with volumetric high-torque hydraulic engine. Operating element feed (DH swings in the horizontal plane) is performed with limited-swing hydraulic engine. Taking into the consideration the specificity of DH layout, the operating element hydraulic engine must be sufficiently compact and provide the necessary cutting power, which is determined by the formula [21]:

$$N_{\text{эф}} = M\omega = Zpb\delta \frac{R_{cm} - R_{pom}}{2}\omega \tag{16}$$

where M - cutting moment on the operating element $(M = P_{рез}\frac{D_{cp}}{2})$, $P_{рез}$ - cutting force, D_{cp} - average diameter of the operating element, ω - angular speed, Z - number of operating chambers in the hydraulic engine, p - pressure in the operating chamber, b - length of the rotor operating part, δ - radial height of the operating chamber, δ - stator radius, R_{pom} - rotor radius.

Stable process of hydraulic hoisting in the ring channel is carried out at a certain area of its cross-section, on the value of which influences the radius of stator, which shall be determined to meet the condition (14) as follows:

$$R_{cm} = 0{,}5\left(D_{\kappa pn} - 2h\right), \tag{17}$$

where h - thickness of the casing wall, which is determined from strength considerations.

The rest engine design parameters are determined by computer approach with the help of *EngineC* program.

Ensuring the specified level of capacity is achieved by use of DH with the vertical axis of rotation of the engine and formation of the ring channel, wherein stable process of hydraulic hoisting of specified particle size nodules takes place. Engine parameters are calculated to meet the power criteria at FMN separation.

3. RESULTS

According to the equations (2) & (3), the dependences of mix flow velocity v_{mix} within the sludge pipe and the critical velocity v_{cr} on the intermediate capsule relative depth $\overline{H}$ shown in Figure-3 are plotted. The equation (7) makes us possible to determine the point A in the graph. [19]

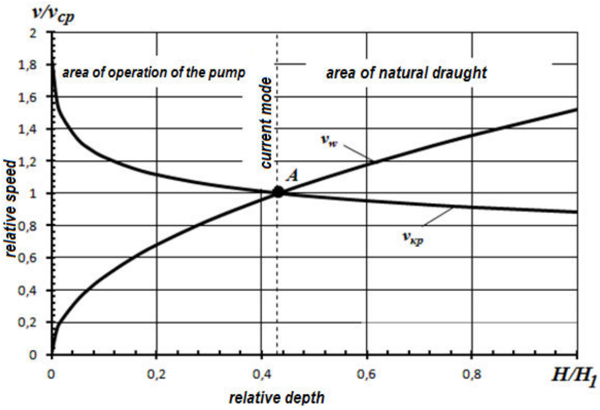

Figure-3. Areas of production system operation.

The results of the mentioned experiment regarding determining K coefficient are presened in Figure-4.

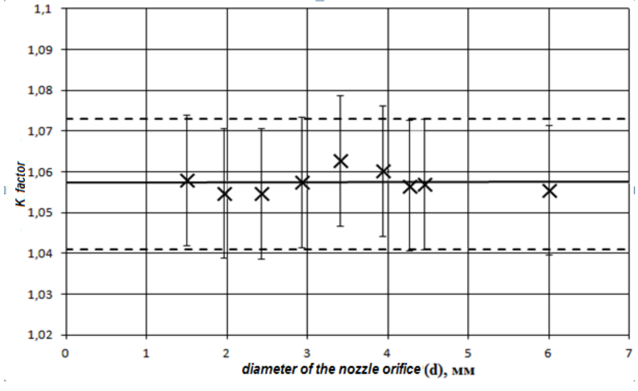

Figure-4. Test results of liquid flowing out into the water (submerged flowing out).

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According to formulas (10) and (11) the diagram of dependence of $N_н\left(\overline{H}\right)$ and $N_{нр}\left(\overline{H}\right)$ is plotted, and according to (8) the diagram of production process energy intensity, as the function of the relative submersion depth $Э\left(\overline{H}\right)$, (Figure-5). Approximation of the curve $Э = f\left(\overline{H}\right)$ gives the parabolic dependence with the correlation factor $R^2 = 1$.

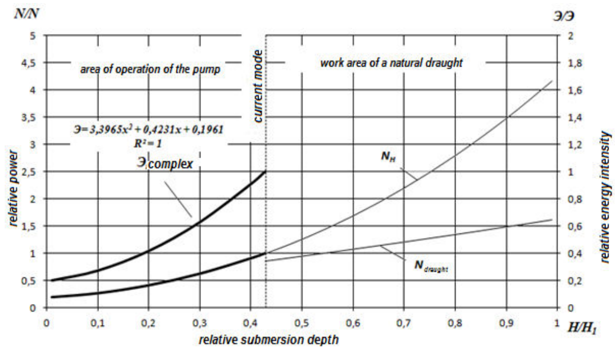

Figure-5. Dependence of the energy intensity of production process and power of the equipment on $\overline{H}$.

The conditions for transportation of nodules through the dredge head ring channel are shown in Figure-6.

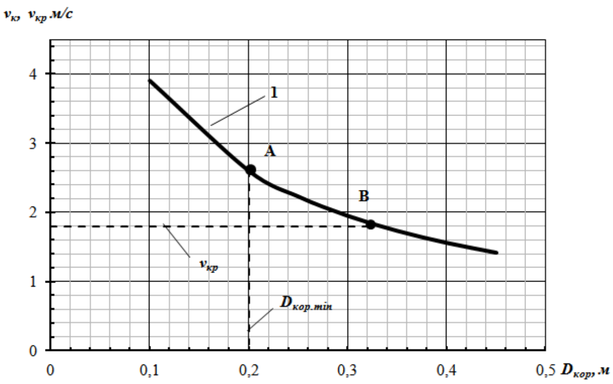

Figure-6. Dependency graph of the pulp speed within the annular channel on the hydraulic motor housing outer diameter.

The dependence of the lifting force being created (which transfers the nodules from the working attachment) on the tubing flange angular velocity (Figure-7) shall be plotted according to expression (14).

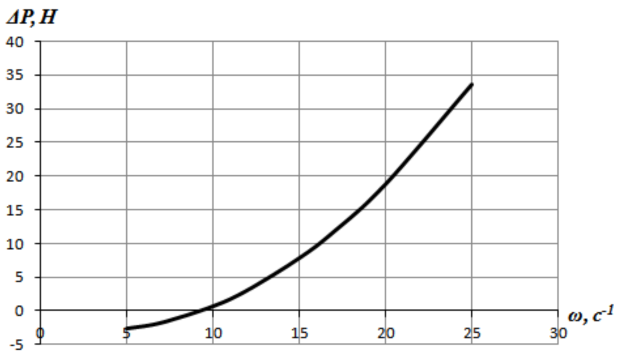

Figure-7. Behavior of the resulting lifting force in case of changing the angular velocity of rotation of tubing flange with rippers.

4. DISCUSSIONS

According to Figure-3, the flow velocity curve to be determined by formula (2) and the critical velocity curve (3) depend on the capsule penetration relative ordinate and intersect at some point *A* at which the condition (1) is satisfied. There are two areas of complex operation. In the first one, to the left of the dotted line, the flow velocity does not exceed the critical velocity, that's exactly why the "hydrolift" effect is absent for FMN of a designated size, and thus in this area the hydraulic hoisting work is performed via a soil pump. At the intersection point of the considered velocities (point *A*), the complex work is fulfilled most effectively (at a constant capacity by the solid weight). In the second field, to the right of the dotted line, the hydraulic hoisting condition is fulfilled, that's exactly why the transportation of hydraulic fluid is carried out by means of natural draft; however, when increasing the capsule penetration relative ordinate, the slurry "dilution" process occurs, which does not affect the complex productivity, but is associated with additional energy costs.

The test results (Figure-4) made it clear that there were additional resistances in case of leaking into the water, which affects the power of the pump feeding the sea-floor equipment. The coefficient K affects the preparation process energy intensity and, consequently, it affects the extraction process total energy intensity. The value of coefficients (12) with due regard to errors was $K = 1.06 \pm 0.016$.

It is apparent from Fig. 5 that when the capsule immersion depth is less than the critical one, when the draft in the pipeline does not provide for raising of nodules with a designated size, the hydrostatic pressure *H* corresponding to this immersion is expended for lifting the conventionally pure sea water through the pipeline to the height H_2, as well as for overcoming the hydraulic resistances of this tract. At the same time, the capacity of the pump unit N_{pu} is used for dewatering only, and the energy intensity is not calculated. Within the transition zone $\overline{H} = \overline{H}_{cr}$, the flow due to natural draught ceases to exist, and a power hydraulic lift begins due to operation of the slurry-pumping equipment (within the capsule) in case of changed sludge pipe resistance due to changing its length. In Figure-5, this state is marked by a power "leap", which has also considered the efficiency rate influence of the equipment within the capsule.

Starting with $\overline{H}_{cr}$ the pump unit works for hydraulic hoisting the pulp with Ferromanganese Nodules (FN) at a dredge head (DH) performance by the weigh G_m (by the volume $Q_{\text{Tv}} = G_m/\rho_s$), and the energy intensity corresponds to the formula (8). When increasing $\overline{H}$, the energy intensity also increases, which is related to energy overexpenditure for lifting a larger quantity of water entering the capsule for a longer distance with a constant value of DH performance, which negates the complex operation effectiveness.

The graphical dependence of the pulp velocity within the DH working attachment annular channel on the hydraulic motor hosing outer diameter, which was calculated using the formula (15) for the specific values of the input quantities, is presented in Figure-6. Point A corresponds to the housing minimum permissible diameter; point B corresponds to the critical velocity of the pulp within the annular space. Section *A-B* of the curve 1 is suitable for use while designing a working attachment. Point *B* corresponds to the design diameter, and point *A* is a floating one and depends on the chosen design solution of the engine flow section. To ensure a preset level of the drag head performance, a need arises in designing a positive displacement high-torque hydraulic motor that meets the power and rotation frequency requirements.

The obtained characteristics curve $\Delta P = f(\omega)$ (Figure-7.) corresponds to the idea of the capability of achieving the required resultant lifting force due to changing the high-torque hydraulic motor shaft rotation speed. Moreover, the lifting resultant force increases with the growth in the engine angular velocity of rotation.

5. CONCLUSIONS

a) The energy intensity of the process of ferro-manganese nodules mining from the shelf by the system with a dredge head having the effective operation regime is described by the parabolic function of the relative depth of intermediate capsule immersion.

b) Effective operation regime of the marine mining system on the shelf, characterized by the depth of intermediate capsule immersion, is determined by the mathematical model taking into consideration the set of variable parameters.

c) Rational parameters of the dredge head, characterized by rock mass and power capacity of the system, are provided by vertical and concentric installation of operating element hydraulic engine in the suction pipeline and the safety catch, which covers the mining zone with formation of the ring channel forming directional flow of the hydraulic mix of specified particle size ferro-manganese nodules.

d) Mechanical characteristics of the hydraulic engine for dredge head drive and local resistances at the drive motor outlet when discharge of the power fluid into the environment (sea water) depend on the factor of discharge K into the water environment, the value of which is equal to 1.06.

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