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Basis of High-pressure Water Jet Implementation for Poly-metallic Concretions Output from the Ocean's Bottom

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1. Introduction

Comprehensive knowledge and modern technique make it possible to reach for different natural resources deposited in water or on oceans bottom or even in stratum below the bottom. World ocean takes over 71% of our globe and considering continuous shrinking of natural resources of raw materials and fuels it becomes nowadays the area of intensive geological exploration. Having in mind the fact that most of typical land resources of useful minerals will last at the very most 50÷200 years, adequate reserves laying down at the bottom of the world sea may give our civilization a chance for several thousand years' development, according to scientist calculations [14].

Taking above into consideration, all seas and oceans shelves were divided into plots and fields. Many shelves are explored nowadays concerning petroleum and natural gas and such output reaching the level of 20% of total production [5]. Basing on different research and exploration it was found that the bottom and under bottom resources of natural minerals are gigantic. Technological development as well as huge investments caused that this XXI century starts new beginning of oceans exploitation [15] and its conquest.

Careful investigations especially of deep resources exploration still is future matter. However nowadays there are rich useful minerals areas deposited at the bottom in the form of poly-metallic concretions. These are o res in the form of nodules including metals e.g.: manganese, cobalt, copper, iron and nickel. Among six different areas rich in concretions, the most perspective one is Clarion-Clipperton where such minerals concentration exceeds 10 kg/m^2 [9]. This area region is located at Pacific in equatorial zone including undersea bottom leap down at the level range of 4200 to 5200 m [12]. Since 1992 Poland as so called investing pioneer (representing international organization Interocenametal) has the right to explore plot in the range of mentioned Clarion-Clipperton region of area of 150.000 km^2 [7].

This paper presents basis of unconventional technology of poly-metallic concretions output by application of high-pressure cavitation water jet [1] with addition of dry ice particles CO_2 as a medium helpful for material loosening form the ground. Such ice particle resistance to hygroscopicity causes that it doesn't have tendencies for lumping and therefore it may keep predicted ability for sublimation. Adequate intensity of this phenomenon [3, 4] in conditions analogical to those existing down at the sea bottom proceeds in a long time [7]. Considering above the gas form of CO_2 may cause proper draught of water flow in elastic transportation pipeline. In turn for vertical transport intensification there is need to use additional air injector.

2. Poly-metallic concretions and their resources

Poly-metallic concretions are recourses of sea bottom including manganese, nickel, cobalt, and copper [14]. They have the form of spherical or some flattened reminding in shape and size old cannon balls. They are naturally occurring practically in seas all around the globe but the most precious one are these oceanic's laying down at the level of few kilometers. The smallest one has the size of sand while the biggest may reach even approximately 500÷700 kg.

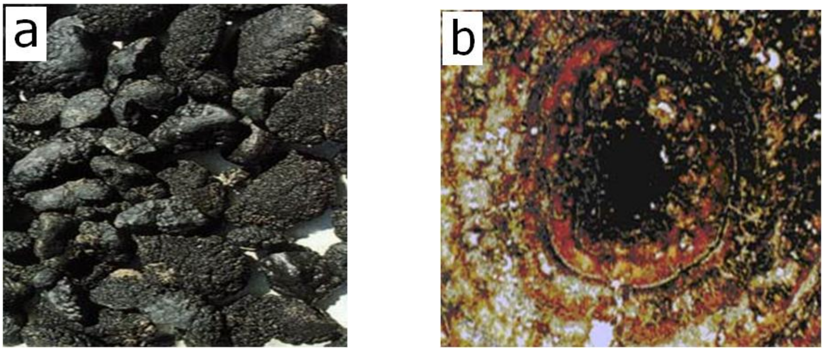

Fig. 1. Concretions (a) got from Clarion-Clipperton area [15] and its cross-section showing out distinct character of its growth (b) [14]
Rys. 1. Konkrecje (a) pozyskane z terenu Clariona-Clippertona [15] i jej przekrój pokazujący odrębny charakter jego wzrostu (b) [14]

Concretions deposits at least in fourth part of oceans mainly at the level range of 3000÷6000 m. However industrial usability has nowadays only six areas located mostly in Pacific bed. Clarion-Clipperton (Fig. 2) is among them a location in equatorial zone where such minerals concentration exceeds 10 kg/m^2 laying down in undersea bottom at the level range of 4200 to 5200 m. Estimated resources located in mentioned Interocenanmetal area of 75.000 km^2 amount to almost 450 million tons including almost 90 million tons of manganese, 4 million tons of nickel, 3.5 million tons of copper, 0.5 million tons of cobalt [9, 12].

Comparing to other areas, such concretions includes also the highest amount of metals (Table 1). Mean contents of main metals are as follows: 25÷28% of manganese, 1.14÷1.25% of nickel, 0.95÷1.1% of copper and approximately 0.21% of cobalt.

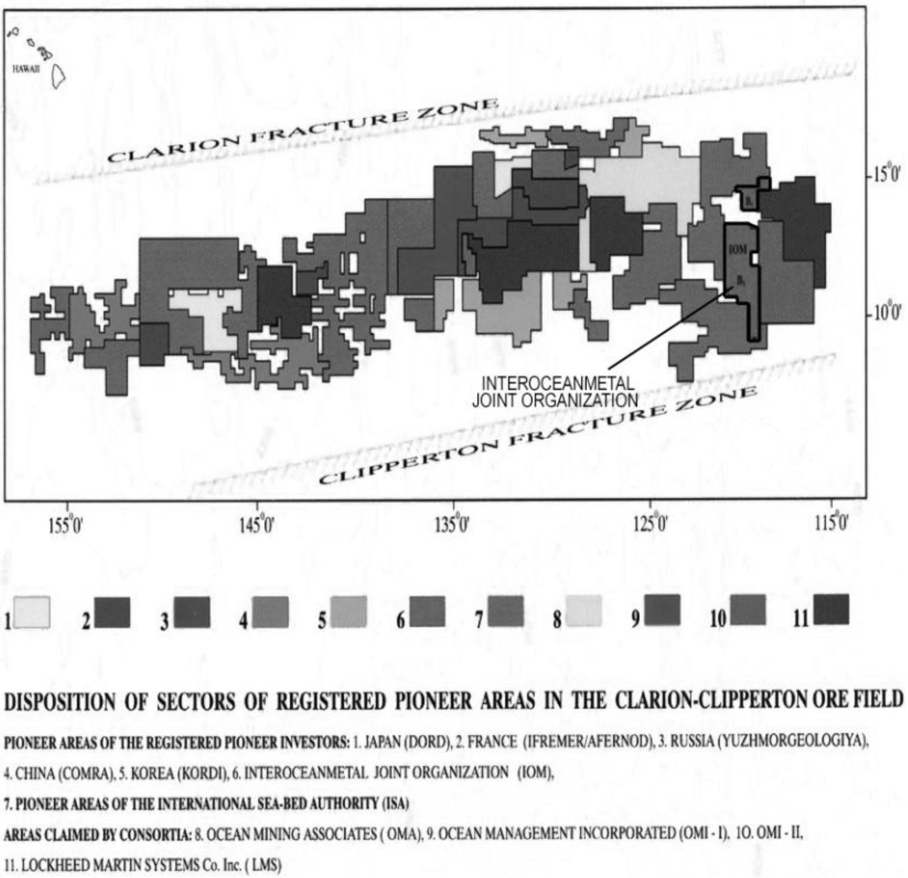

Fig. 2. A map of pioneers' investors' localization in Clarion-Clipperton area [15]
Rys. 2. Mapa pionierskich inwestycji na obszarze Clariona-Clippertona [15]

Table 1. Percentage statement of poly-metallic concretions chemical composition origin of Clarion-Clipperton area
Tabela 1. Procentowy skład polimetalicznych konkrecji pochodzących z rejonu Clariona-Clippertona

symbol	contents [%]	density for 20°C [g/cm^3]	unitary weight [g/cm^3]
Mn	30.72	7.2	2.21184
O	28.34	0.001428	$0.40495 \cdot 10^{-3}$
Si	15.67	2.33	0.365111
Fe	6.1	7.87	0.48007
Al	4.96	2.7	0.13392
Na	3.38	0.97	0.032786
Mg	3.23	1.74	0.056202
Ca	2.51	1.55	0.038905
Ni	1.28	8.9	0.11392
K	1.26	0.86	0.010836
Cu	1.22	8.96	0.109312
Ba	0.28	3.65	0.01022
Ti	0.24	4.51	0.010824
Co	0.18	8.9	0.01602
P	0.15	0.86	0.00129
Zn	0.15	7.13	0.010695
S	0.14	2.06	0.002884
V, Mo, Pb, Zr, Ce, As, Y, Nb, La, Yb, Ga, Ir, W, Be	together 0.29	----	0.004524
altogether	100	approx. 3.6	3.609764

3. Problem of concretions output

Basic problem of all mining methods is not even connected with mining, minerals separation but their transportation to the surface platform. Such problem concerns especially to deep-sea mining of poly-metallic concretions [18]. Typical mechanical forms of mining have no chance to be applied there because these complicated methods realized in such deep are often disappointing. Therefore it is worth to develop mainly the method of hydraulic transportation that consist in water flow intensification in the pipeline by additional air-injector (Fig. 3) application.

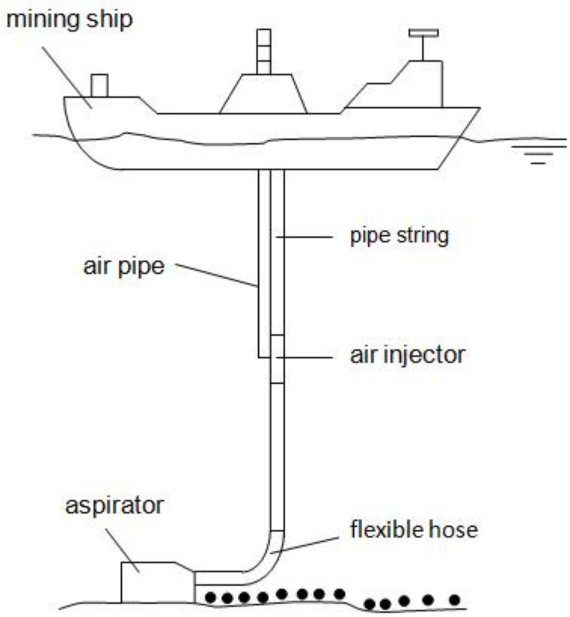

Fig. 3. Idea of HPWJ-mining and hydraulic transportation of concretions using air-injector
Rys. 3. Zasada wydobycia i hydraulicznego transportu konkrecji z zastosowaniem wysokociśnieniowej strugi wodnej z pomocą powietrza

An air lift system shown in Fig. 3 compressed air is used as lifting power, which is injected into the pipe string via an injector in some depth. Because of the different densities of outside seawater and inside multiphase mixture and the buoyancy and expansion of the compressed air in the pipe, the nodules are sucked and transported from the bottom to the surface. The flow manners in the pipe are a CO_2 gas-nodule-water 3-phase flow below the injector and an air-nodule-water 3-phase flow above. Such transportation has a lot of advantages and let to construct mining ships [17] with great efficiency and range and relatively small power consumption. Therefore it is important in such conditions to intensify output transportation starting from sucking in system (Fig. 4).

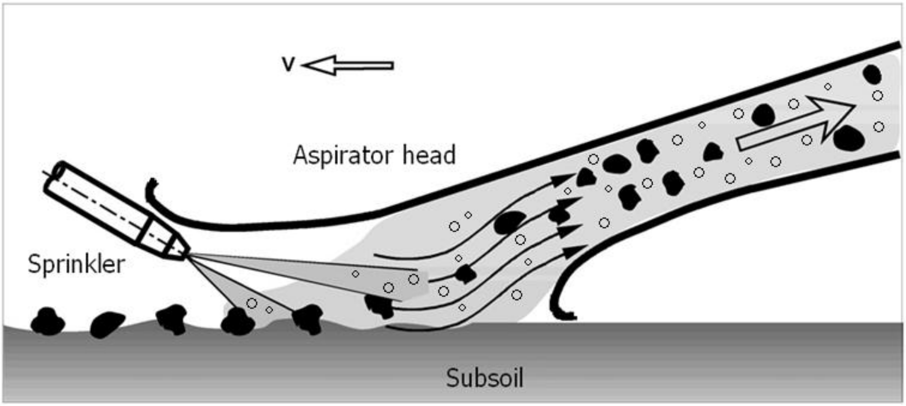

Fig. 4. New working system (aspirator head) of concretions sucking
Rys. 4. Nowy system zasysania konkrecji (głowica aspiratora)

It might be realized by cavitation effect [1] and by dry ice particles CO_2 addition to high-pressure water jet being elastic mining tool. This ice selection is caused of two very important its features: resistance to hygroscopicity and ability for sublimation [3, 4]. Such ice pellets resistance to hygroscopicity causes that it doesn't have tendencies for lumping and therefore it may keep predicted ability for sublimation during flow in water jet. The gas form of CO_2 sublimates down in the mining zone causing proper draught of water flow in elastic pipeline carrying out nodules up to the surface [7].

Therefore practical usage of such properties of dry ice pellets needs to determine their intensity of sublimation is such conditions.

4. Dry ice pellets (CO_2) sublimation effect

The most dominant factor deciding of flow dynamics in vertical pipeline system is intensity of dry ice pellets CO_2 sublimation what finally is connected with suction force of concretions output.

Dry ice pellets CO_2 accelerated in a high-pressure water jet collide each other and with internal surfaces of pipes and a sprinkler. Dry ice pellets CO_2 in consequence of all these collisions undergo a partial sublimation, and therefore such the high-pressure ice-water jet "smokes" with gas CO_2. However, the most intensive sublimation of dry ice pellets CO_2 occurs in an erosion zone because of the collision with the concretion surface. Thus, the prominent deformation ice-pellet volumes or their disintegration causes that the process of sublimation is taking its course very rapidly, usually nearly explosive in character. The impetuosity of this process results from the fact that gaseous CO_2 for the physically normal conditions is 800 times larger in volume than when it is in the form of dry ice pellets [3, 6].

Considering this specific character of the ductile impingement of dry ice pellets CO_2 onto the concretion surface one can assume that kinetics energy of that pellet is totally transformed into the energy of the ice sublimation [2, 8]. That makes it possible to determine the sublimated volume of dry-ice pellets in the course of that collision. It is expressed by the following relation:

$$z = \frac{E_k}{C_s m_i}. \tag{1}$$

Taking above into consideration, it was found that depending on the pressure of water the volume of dry-ice pellets was sublimated within 1.4÷7.3% [3]. Then, the volume of gas CO_2 received from a sublimated dry-ice pellet for the physically normal conditions is expressed by the following formula:

$$V_g = \frac{V E_k}{C_s m_i} \delta \cdot w. \tag{2}$$

Real physical conditions occurring at the ocean bottom are greatly different than normal once what causes that the real volume of generated CO_2 gas is considerably smaller. However classical physics gives no chance to determine such volume. One could expect that it should be great volume of gas CO_2 generated rapidly in the contact area of dry-ice pellets with the concretion surface produces a very dynamic increase in the hammer water effect. Such one causes rapid water pressing in pipeline transporting output to the surface.

As it comes out from above data that hydro-jetting drive of this ice gives a chance for only small percentage utilization of sublimation effect potential intensity. In order to multiplication the dynamism of output flow one should increase sublimation effect intensity directly in mining zone. As it comes out from the analysis [7] potential increase of transportation efficiency resultant from such ice kinetic energy increase doesn’t reach the level of 25%. Therefore it is necessary to elaborate such specific physical conditions or to use adequate chemical catalysts to multiply intensity of this phenomena occurrence.

5. Theoretical basis of the method of poly-metallic concretions output

5.1. Simulation model of poly-metallic concretions output

Thanks to dry ice pellets sublimation effect a considerable amount of CO_2 gas phase occurs causing gas-water-nodules mixture lifting inside the pipeline. However such mixture of water and output – created in the aspirator – has ability to be lifted on a certain height because its increase leads to decrease of nodules convection effectiveness [7]. In order to intensify such process a compressed air should be pressed in the pipeline on a specified depth increasing this way the lifting power. Mixture flow takes place because of pressure difference and as a consequence of buoyancy as well as effect of compressed air expansion inside the pipeline. Thanks to that the mixture of seawater, output and air is lifted up to the surface of mining ship.

Efficiency of the output is a consequence of the depth of air-injector connection to the main transportation pipeline but moreover it results from the air amount and its pressure. In respect of this important feature one should take into consideration adequate choice of these most important parameters effecting in the whole process effectiveness.

A model of such output method, simplified for theoretical consideration purposes is presented in Fig. 5.

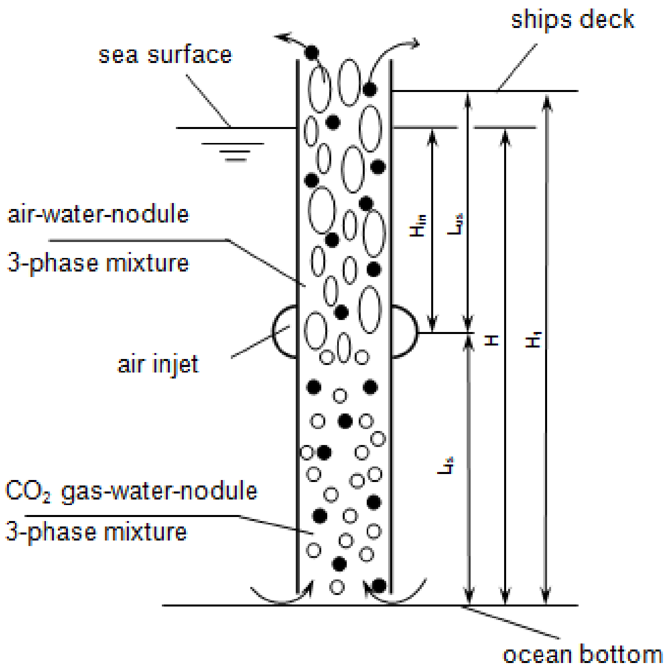

Fig. 5. Model of hydraulic with air-injector transportation of poly-metallic concretions
Rys. 5. Model transportu hydraulicznego polimetalicznych konkrecji z wspomaganego powietrzem

5.2. Theoretical model of the flow inside transporting pipeline

According to 3-phase flow of gas-liquid-solid, one can assume in approximation that it is a 2-phase flow of gas-liquid while mentioned liquid phase creates seawater including some inclusions of solid (concretions). Usually a model of such 2-phase (gas-liquid) flow is characterized with bubbles structure. Such a model can also be used for the analysis of metallic nodules. Analysis of such flow, ensuring effective lift of poly-metallic concretions can be expressed with the following equations [18]:

For bubble-slug flow transition:

$$Fr_{go} = 0.0061 + 0.007\ Fr_{lo} \tag{3}$$

For froth-slug flow transition:

$$Fr_{go} = 0.136 + 0.022\ Fr_{lo} \tag{4}$$

where: Fr_{go} and Fr_{lo} are Froude Numbers for gas and liquid respectively, and:

$$Fr_{go} = \frac{v_{go}}{\sqrt{gD\frac{\rho_1}{\rho_g}}} \tag{5}$$

$$Fr_{go} = \frac{v_{lo}}{\sqrt{gD}} \tag{6}$$

In turn free settling velocity (v_{so}) is an important physical property of nodule which could be determined by experiments and expressed by the following empirical equation [13]:

$$v_{so} = 2.754 \cdot \sqrt{gd_s\left(\frac{\rho_s}{\rho_l} - 1\right)} \tag{7}$$

where:
g – acceleration due to gravity,
d_s – weighted mean diameter of nodules,
ρ_s – nodules density,
ρ_l – sea-water density.

In order to achieve feasibility lifting of nodules the mean water velocity v_l in the mixture must be larger than the nodule free settling velocity v_{so}. On the other hand, however, the larger the v_l the more the pressure drop due to friction. Generally, a minimum v_l equal two times of v_{so} is considered [11], i.e.:

$$v_l \geq 2v_{so} \tag{8}$$

Equation (8) is suitable for both 2-phase and 3-phase flows. For a given 2-phase lift system with certain amounts of annual nodule production p, pipeline diameter D, and nodule concentration c, the equations below must also be followed [18]:

$$v_{l\ 2} = v_{m2} + c_{sp} v_{so} \quad . \tag{9}$$

where:
c_{sp} – spatial concentration of nodules
v_{m2} – 2-phase flow velocity, which can be calculated according to the following empirical equation:

$$v_{m\ 2} = 1471.65 \frac{P}{c_t \rho_s D^2 T} \tag{10}$$

where:
P – annual nodules production,
c_t – delivered concentration of nodules,
D – inner diameter of pipe,
T – annual working days.

$$v_{s2} = v_{l2} - v_{so} = v_{m2} - (1 - c_{sp}) v_{so} \tag{11}$$

$$c_{sp} = -0.5\left(\frac{v_{m2}}{v_{so}} - 1\right) + \left[0.25\left(\frac{v_{m2}}{v_{so}} - 1\right)^2 + c_t \frac{v_{m2}}{v_{so}}\right]^{0.5} \tag{12}$$

5.3. Minimum injection depth (H_{in})

Considering critical depth in a pump lift system, there is a minimum injection depth H_{in} an air lift system which could be determined from the following balance equation [18]:

$$\rho_l g H = \rho_{m2} g \left(H - H_{in}\right) + \frac{v_{l2}^2}{2g} + \lambda_m \frac{H - H_{in}}{D} \cdot \frac{v_{l2}^2}{2} \rho_{m2} \tag{13}$$

Converting above equation one can define minimum injection depth as:

$$H_{in} = H\left(1 - \frac{\rho_l}{\rho_{m2}} \frac{2gD}{2gD + \lambda_m v_{l2}^2}\right) + \frac{D v_{l2}^2}{\rho_{m2} g (2gD + \lambda_m v_{l2}^2)} \quad . \tag{14}$$

In equations (13) and (14), λ_m is a friction factor for mixture flow which would be expressed by:

$$\lambda_m = \lambda_l (1+\lambda_r) \tag{15}$$

where λ_r is a relative friction factor which could be determined by the empirical equation [10]:

$$\lambda_r = 48.9 \cdot \left(\frac{d_s}{D}\right)^{2.1} \left(\frac{v_l}{gd_s}\right)^{-1.6} \mu_s^{0.7} \left(\frac{\rho_s}{\rho_l}\right)^{2.0} \tag{16}$$

where μ_s is load ratio, $\mu_s = \dfrac{m_s}{m_l}$

5.4. Pressure drop (p_t)

In an air lift system, total pressure drop of the 3-phase flow mixture comprises three parts [18], i.e.:

$$p_{t3} = p_{h3} + p_{ac} + p_{f3} \tag{17}$$

- Gravity loss, p_{h3}:

$$p_{h3} = f_{l3} L_{us} \rho_{m2} g = f_{l3} L_s [\rho_l + c_{sp}(\rho_s - \rho_l)] g \tag{18}$$

- Acceleration loss (p_{ac}):

$$p_{ac} = \frac{G_{ls}}{g}(v_{ls2} - v_{ls1}) + \frac{G_g}{g}(v_{g2} - v_{g1}) \tag{19}$$

- Friction loss (p_{f3}):

$$p_{f3} = \lambda_m \frac{L_{us}}{D} \cdot \frac{v_{l3}^2}{2g \cdot f_{l3}} \rho_{m2} \cdot g \tag{20}$$

Occurred in above equation volumetric fraction f_{l3} of liquid-solid portion in a 3-phase flow varies with gas and water velocities and locations along the pipe. It is generally expressed by a mean value in the pipe [18], i.e.:

$$f_{l3} = 1 + \frac{\frac{v_{go}}{v_{b3}}}{\frac{L_{us}\sigma}{10}\left(1 - 1.2\frac{v_{go}}{v_{b3}}\right)} \cdot \ln \frac{1}{1 + \frac{L_{us}\sigma}{10}\left(1 + 1.2\frac{v_{go}}{v_{b3}}\right)} \tag{21}$$

Besides that, occurred here bubble velocity (v_{b3}) can be calculated as:

$$v_{b3} = \frac{1.2 \cdot \left(Q_s + Q_l + Q_{go}\right)}{A} + 0.35\sqrt{gD} \tag{22}$$

An empirical equation for f_{l3} is also gained by experiments [16]:

$$f_{l3} = a_3 \exp(b_3 Fr_{g3}) \tag{23}$$

where Fr_{g3} is a Froude Number, Expressem as follows:

$$Fr_{g3} = \frac{v_{go}}{\sqrt{2gL}} \tag{24}$$

where: a_3 and b_3 are experimental factors.

5.5. Air flow rate (Q_{go})

The injecting air flow rate Q_{go} (under atmosphere) determines the apparent velocity of air v_{go} and it influences significantly the lifted nodule rate Q_s when the nodule concentration keeps constant. The relation between Q_{go} and Q_s could be found indirectly from equation (21) and (22).

5.6. Lifting power consumption and efficiency

Power consumption on lifting nodules for an air lift system:

$$N_1 = Q_s (\rho_s - \rho_l)\, g\, (H_s + L_s) + \rho_s\, g\, (L - H_s) \tag{25}$$

Power consumption by compressed air:

$$N_2 = p_a Q_{go} \ln \frac{p_t}{p_a} \tag{26}$$

Efficiency on air lifting:

$$\eta = \frac{N_1}{N_2} = \frac{Q_s(\rho_s - \rho_l)g(H_s + L_s) + \rho_s g(L - H_s)}{p_a Q_{go} \ln \frac{p_t}{p_a}} \tag{27}$$

6. Conclusions

Presented paper characterizes poly-metallic concretions deposited at the ocean bottom and its resources and their appearance areas. Main problems connected with iron-manganese concretions output in a worldwide scale are discussed in too. This matter is important in world technique because of expected advantages resulting from this minerals output. It is important at this stage of process development to overcome important conception and technical problems enabling future projecting of effective systems and mining mechanisms. Besides extreme technical conditions such systems must have ensure a lot of conditions connected with ecosystem hazard in global scale of world-ocean.

This paper discuss possibilities of high-pressure water jet application admixed with dry ice pellets CO_2. As presented in, such ice addition is favorable thanks to the fact that it doesn't have tendencies for lumping but sublimate in mining zone. Generated this way gas phase of CO_2 increases dynamics of output vertical flow inside the pipeline and increases the same efficiency of its transportation to the surface.

Basis of air-injection lift system elaborated in order to optimize poly-metallic concretions output are presented in. One can also find an analysis of flow structures occurring in different cross-sections of the lifting pipeline as well as there were defined their theoretical dependences. There were also elaborated some equations enabling to choose the most important parameters that decide of the method effectiveness. Thanks to all that, as it occurred, the efficiency of poly-metallic concretions lifting strongly depends on the air amount and its pressure delivered to transporting pipeline as well as on the depth of air-injector installation.

Nomenclature

c – concentration of nodules,
d_s – weighted mean diameter of nodules [m],
f – average volumetric fraction,
g – acceleration due to gravity [m/s^2],
m – mass flow rate [kg/s],
m_i – dry-ice pellets mass [g],
p – pressure; pressure drop [p_a],
v – velocity [m/s],
w – coefficient of multiplying gas-solid CO_2 volume,
z – coefficient of sublimated ice pellets piece volume,
C_s –sublimation heat of dry-ice pellets CO_2, [J/g]
D – inner diameter of pipe [m],
E_k – kinetic energy of dry-ice pellets [J],
G – weight flow rate [N/s],
H – submerged length of pipe string; depth; height [m],
L – length of pipe section [m],
N – power [W],
P – annual nodules production [t/y],
Q – volumetric flow rate [m^3/s],
T – annual working days [d/y],
V – volume of dry-ice particle CO_2 [mm^3],
V_g – CO_2 gas volume of sublimation process [mm^3],
δ – effectiveness of sublimation process,
μ – load ratio,
λ – friction factor,
ρ – density [kg/m^3],
η – lifting efficiency,
σ – submerged ratio = H_{in}/L_{us}.

Subscripts

a – atmosphere,
ac – acceleration,
b – bubble,
cr – critical,
f – friction,
g – gas (compressed air),
in – injection,
l – liquid (seawater); lifting,
ls – lower section,
m – mixture,
o – free settling; apparent,
r – relative,
s – solid (nodule),
sp – spatial,
t – delivered; total,
us – upper section,
1 – in; input,
2 – 2-phase flow; output,
3 – 3-phase flow; output.

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Podstawy stosowania wysokociśnieniowej strugi wodnej do wydobywania konkrecji polimetalicznych z dna oceanicznego

Streszczenie

W pracy scharakteryzowano konkrecje polimetaliczne zalegające dno oceaniczne oraz ich zasoby i miejsca występowania, zwłaszcza w przyznanym Polsce obszarze pomiędzy uskokami dna pacyficznego o nazwie Clarion-Clipperton. Przeanalizowano metody ich wydobywania w obszarze głębokomorskim a zwłaszcza hydraulicznego transportu urobku z dna oceanu na pokład statku górniczego. Przeanalizowano możliwość zastosowania wysokociśnieniowej strugi wodnej wspomaganej fizycznym oddziaływaniem cząstek suchego lodu CO_2. Wskazano na bardzo przydatne cechy tego lodu, dzięki którym jego cząstki nie podlegają zbrylaniu natomiast sublimują w strefie urobku. Powstające duże ilości gazowej fazy CO_2 zwiększają dynamikę pionowego przepływu płynu w przewodzie rurowym, co zwiększa skuteczność transportu urobku na powierzchnię. Jednak dla zapewnienia odpowiedniej wydajności pionowego transportu konkrecji polimetalicznych należy na określonej głębokości wtłaczać do rury sprężone powietrze. Przedstawiono w nim podstawy transportu metodą injekcji pneumatycznej opracowane dla optymalnego wydobywania konkrecji polimetalicznych. Przeanalizowano struktury przepływów występujących w różnych przekrojach rury transportowej oraz określono ich teoretyczne zależności. Opracowano również wzory pozwalające na dokonywanie wyboru najważniejszych parametrów decydujących o skuteczności tej metody.