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TECHNOLOGICAL COMPLEX FOR PRODUCTION, TRANSPORTATION AND STORAGE OF GAS FROM THE OFFSHORE GAS AND GAS HYDRATES FIELDS

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ТЕХНОЛОГІЧНИЙ КОМПЛЕКС ВИДОБУВАННЯ, ТРАНСПОРТУВАННЯ ТА ЗБЕРІГАННЯ ГАЗУ МОРСЬКИХ ГАЗОВИХ І ГАЗОГІДРАТНИХ РОДОВИЩ

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ABSTRACT

Purpose. Substantiation and development of schematics acceptable for the existing technological methods of natural gas production and transportation from the offshore fields of gas or gas hydrates. Improvement of their efficiency by way of maximum reduction of energy consumption as the result of complex consideration of thermal and physical properties and parameters of the system components interaction in the deposit under development.

Methods. Analysis and generalization of the results of complex experimental research performed on the multifunctional laboratory gas hydrate installation.

Findings. The technology of gas hydrates extraction from the productive reservoir without energy consumption for the phase transition is proposed. It is proved that simultaneous development of gas hydrate fields and gas fields via binding free gas into gas hydrate by ensuring necessary temperature and pressure conditions during gas passing through the sea waterbody is expedient. The feasibility of combining in one chain the proposed technology of the developing the offshore gas and gas hydrate fields with technology of gas transportation in hydrate form and its preservation in ground storages is proved.

Originality. It was substantiated that gas hydrates can be extracted from the productive reservoir without energy consumption for dissociation, by creating conditions of its recrystallization as a result of joint actions of submerged jets of sea water in the mixture with abrasive material and pressure fluctuations.

Practical implications. The proposed gas hydrate technology creates important prerequisites for the development of small and medium remote gas deposits (including gas hydrate ones), the network of ground hydrates storages, improves the efficiency and competitiveness of technology for marine transportation of natural gas in hydrate form

Keywords: *gas hydrates, natural gas, gas hydrate layer, dissociation, concentration, phase transition, gas hydrate blocks*

1. INTRODUCTION

Natural gas consumption in the world is growing, while its easily accessible reserves are depleting rapidly. However, about 80% of gas fields, recently exposed in the world, are relatively small or remote from the transport infrastructure. Most of them are located on sea shelves (in the form of traditional deposits and in hydrate form). Thus, the existing technologies of their development do not contribute to the rational use of a substantial part of their resources (e.g., construction of pipelines can be economically unjustified).

Under certain conditions of temperature and pressure, water molecules and low molecular components of natural gas tend to form relatively stable compounds – gas hydrates. This property results in the fact that in the depths of the Earth and waters of the World's ocean, there occur almost unlimited resources of natural gas in solid hydrate form which are available in most countries (Bondarenko, Sai, Ganushevych, & Ovchynnikov, 2015). Gas hydrates are crystalline compounds (clathrates) of general formula $M \cdot nH_2O$, where M is a molecule of gas-forming hydrate; n – the number that describes the composition and depends on the conditions accompanying formation of gas hydrates $(n = 6 - 17)$. One volume of water contains 70 – 210 volumes of gas.

Potential worldwide resources of gas hydrates are estimated at $2.1 \cdot 10^{16}$ m^3 (Kvenvolden, 1993). Approximately 98% of them are concentrated in the World Ocean at depths ranging from 200 to 700 meters, and in the bottom sediments with thickness of 400 – 800 m. Hence, their development does not require drilling of the ultra-deep wells.

In the Black Sea area, gas resources in the hydrated state are estimated at $25 \cdot 10^{12} – 70 \cdot 10^{12}$ m^3 (in the economic zone of Ukraine – $7 \cdot 10^{12} – 20 \cdot 10^{12}$ m^3) (Vasilev & Dimitrov, 2002).

Natural gas hydrates are distributed across the planet more evenly than sources of oil and gas. Wide introduction of their technology development can result in unreasonable import of natural gas from other countries. Thus, natural gas hydrates will play an important role in the global energy balance as one of the major unconventional resources in the near future.

Analysis of the data concerning as of today known gas hydrates manifestations and their traces in the World Ocean and lakes allows to conclude that underwater gas hydrates can form clusters, which are located at great sub-bottom depths (hundreds of meters) and are controlled by the zones of percolation in conditions of distributed fluids filtering, or are located in the close proximity to the sea floor, at the bottom or at very shallow sub-bottom depths (first meters).

Most of hydrates are present in coarse-grained sedimentary deposits, but during the research, hydrates were also found in fine-grained sediments as small interlayers, lenses and thin rake veins. For example, the study of NGHP-01-10 well detected a powerful range of fractured clays, the hydrates content of which is among the highest in the world (Collett, 2014).

Formed in reservoir conditions, hydrated crystals can be dispersed in the pore space both without destroying pores and with their destruction. They may take the form of 5 – 12 cm particles, of small size lenses and of well-preserved, purely hydrate layers of great length and thickness to a few meters.

There are three basic methods of extracting gas from gas hydrate-bearing layers: lowering the pressure below the equilibrium hydrate formation at a designed temperature, heating hydrate-containing rocks to temperatures higher than equilibrium and their mechanical disintegration. Also there are solutions that suggest using the reagents to influence chemical activity of water and gas, causing a shift in the equilibrium of formation and dissociation reactions of gas hydrates to the lower temperatures zone (the so called inhibitors: methanol, ethylene glycol, electrolyte solutions, etc.). Most of the presently known methods for gas hydrate deposits development suggest a combination of the above methods.

Classic examples of thermal methods for gas hydrate deposits development is the US Patent 6192691 suggesting hot water injection under the dome for gas collecting, installed over the bottom gas hydrates accumulation, and patent application US 20050161217 which suggests electric heating of a productive reservoir and extracting the gas released through the production well. The international application WO 2007/136485 suggests that gas hydrate reservoir be heated by means of laser radiation energy. An example of the combined action on a gas hydrate reservoir (in this case thermal energy and inhibitors are meant) are patents US 4.424.866 and US 6.733.573.

However, the disadvantage of thermal methods for gas hydrate deposits development is concerned with significant energy consumption. Thus, besides the relatively small energy consumption for gas hydrates dissociation (about 7% of the extracted gas combustion energy), most of them will be used to heat hydrate saturated stratum and the rocks in its floor and roof. Moreover, considering the thermal and physical properties of rocks and gas hydrates, it is obvious that the heat action zone in the reservoir will be limited to a few meters.

The most lucrative technology of gas hydrate deposits development in terms of energy costs is reducing the reservoir pressure below the equilibrium, followed by free gas extraction. An example of the above method is described in international application WO 2007/072172, which suggests reducing pressure in the gas hydrate reservoir by degassing lower horizons.

However, this method is available for deposits, where hydrates saturation is insufficient and the reservoir has sufficient gas or water permeability. Naturally, hydrate saturation growth (and, hence, permeability reduction) diminishes the above method's efficiency.

Another disadvantage of the said method, based on reducing pressure in the hydrate bearing reservoir, is associated with the secondary anthropogenic formation of hydrates in the bottom-hole formation zone due to the Joule – Thomson effect and the effect of hydrate self-preservation in a layer. For example, for the initial temperature of the reservoir 283 K and 5.74 MPa pressure, Joule – Thomson coefficient is 3 – 4 K at 1 MPa depression. Thus, at the depression of 3 – 4 MPa, the bottom-hole temperature may reach the water freezing point. The process is additionally complicated by the fact that rocks containing over 60% of hydrate are virtually gas impermeable (Basniev, Kul'chitskiy, Shchebetov, & Nifantov, 2006). As a result, gas hydrate (hydrate layer) will be "reliably" preserved by the ice layer for a long time, which will depend on the speed of heat supply and will be determined by its own thermo-physical properties and those of the surrounding rocks in the floor and roof.

In addition, the results of experimental research into gas filtration through hydrate saturated rocks presented in (Beznosikov & Maslov, 1975), indicate that the permeability of gas is two, three or more orders of magnitude less than the permeability of samples unsaturated by hydrates. Low permeability is associated with initial water saturation because at its certain values, gas hydrate is formed in all the volume of the porous medium, filling all pores and micro-cracks.

In addition, gas hydrates could serve as "cement" for particles of the bed rock. Dissociation of clathrates in sediments causes abnormally high porosity and releases large masses of water (Kvenvolden, 1993). Thus, destabilization of gas hydrates will lead to a significant weakening of sedimentary structures in the dissociation zone. Therefore, destruction of a gas hydrate structure by reducing the pressure, raising temperature or introducing inhibitors may lead to decompaction of the hydrate-cemented rocks and transform them into an over wetted unstable structure with gas bubbles inclusions. Due to the depression, created for gas extraction, the over wetted stratum will be inevitably destroyed and unlimited amount of rock together with water and gas will be carried into the well, making its further exploitation practically impossible.

There are also ways to simultaneously reduce pressure and heat supply to wells. Moreover, hydrate dissociation in the reservoir happens mainly due to lower pressure; and heat, supplied to the bottom-hole, permits reducing the zone of secondary hydrate formation, thus positively affecting the gas jet rate. However, a combination of these methods does not solve the above problems.

Methods presented in applications US 2008/0088171, WO 00/47832 and RU 2004106857/03 suggest open-cut mine development of marine gas hydrate deposits by their mechanical disintegration. Thus, the method of extracting bottom hydrate-containing sediments by underwater excavation, their lifting to the surface in containers and accumulation of the received gas under the dome located in the ship's bottom, is described in the application US 2008/0088171.

The method of extracting gas hydrates from the seabed, described in the application RU 2004106857/03, suggests using an extraction device in the form of a self-propelled header and a device delivering gas hydrates to the surface in the form of a barge independently emerging to the surface.

The method of extracting bottom and sub-bottom hydrates described in the application WO 00/47832, ensures destruction of gas hydrate layer by compressed air and special high-density solution (or pressured water), fed through the pipe, separation of hydrate pieces from the bottom, their collection and dissociation. The possibility of heating the compressed air and fluid is also stipulated. However, since the surface of gas discharge areas located near the bottom gas hydrates' deposits is mainly covered with a layer of sediments (often submarine hydrates, starting from the depth of 0.4 to 2.2 m below the bottom surface (Shnyukov, Gozhik, Krayushkin, & Klochko, 2007), and depth of their cutting resulting from the rate of jet energy attenuation in the aquatic environment is insignificant, effectiveness of this method will be questionable.

This also applies to the case, characteristic for most deposits of gas hydrates – the ratio of gas hydrates volume to the mineral part is insignificant (hydrates fill the pores or become cements of the mineral part of the layer). So, using the method suggesting gas hydrates disintegration by means of air or liquid jets, and also using the quarry rock cutting machinery located directly on the seabed, will be inefficient.

2. THE MAIN PART

2.1. Analysis of the borehole hydro-mining technology

In mining industry, the method of minerals' hydro-mining (Arens et al., 2007) is well known, it stipulates drilling the well in the deposit field, reducing the density of rocks in the place of its location by means of transferring it into a moving state by means of a hydraulic monitor jet and extracting the hydraulic fluid (pulp) to the surface. Analysis of technological operations of the borehole hydraulic mining (bearing of the productive strata, hydraulic-ablation formation of pulp, transportation from the unit to the inductive apparatus, raise of the hydraulic-mixture to the surface, enrichment) and consistency of their implementation has shown perspectives of this method incorporation in order to develop gas hydrate deposits.

Hydraulic method is used to separate rocks from the mass with the help of water jets ejected by hydromonitor apparatuses, whose main task is formation and direction of these jets. The hydraulic-production aggregate, which represents a combination of borehole jet and hoisting and transport mechanism of the borehole for extracting the pulp to the surface, is mounted in a borehole. The static water pressure is transformed into the kinetic energy of the jet in the hydromonitor. The rate of water increases as a result of decrease in of the nozzle cross section at the constant level of its expenditure (the potential energy of water in the nozzle is converted into kinetic energy whose store is diminishing with distance from the nozzle). In this case, in the technology of borehole hydraulic production, jet is a working organ for destruction and transportation of rocks.

The mechanism of the primary hydraulic destruction process is characterized by versatile impact of water on the mass which includes destruction via shear stresses, hydraulic shock, filtration, pressure (Rehbinder, 1980), and at every point it is described by the following formula:

$$\tau \geq \left(c_t - c_p\right) + \left(\gamma H \cdot 10^{-2} tg\varphi_t - K_l \gamma H \cdot 10^{-2} \lg\varphi_p\right), \quad (1)$$

where:

τ – destructive shear stresses, MPa;

c_t – temporary adhesion (maximum), MPa;

c_p – prolonged adhesion, MPa;

φ_t – temporary angle of internal friction, °C;

φ_p – prolonged angle of internal friction, °C;

γ – density of rocks, kg/m^3;

H – depth of development, m;

K_l – coefficient of lateral pressure.

Thus by penetrating into the mass at the expense of filtration through pores and cracks, water lowers the strength of rocks (Rehbinder, 1980), causes local hydraulic fracturing and destruction. This should be taken into consideration by adjusting the above dependence while studying the mechanism of a particular mass degradation and introduction of appropriate coefficients. But the process of jets movement in multiphase systems (water, solid inclusions, gas) is associated with phenomena so complex that sufficiently reliable methods of their analytical determination do not exist as of today.

2.2. The method of gas hydrate deposits development

Considering disadvantages of the technology introduced above, another method of marine gas hydrate development of deposits (Fig. 1) is proposed, which provides:

– exposure of average gas-hydrate stratum by horizontal boreholes, of the thick stratum – by vertical wells or the ones obliquely directed to the their bottom *7*;

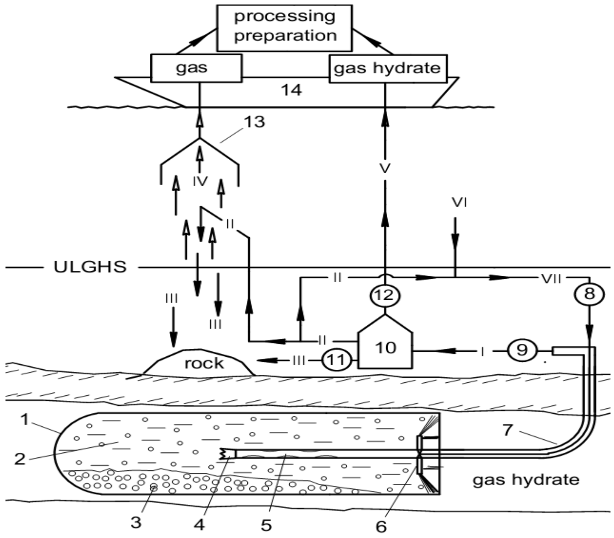


Figure 1. Principal diagram of the method for marine gas hydrate deposits development: ULGHS – the upper limit of gas hydrate stability; 1 – excavation in the hydrate-saturated reservoir; 2 – water-hydrate mineral pulp; 3 – sediment of rock; 4 – drill bit; 5 – pulp intake; 6 – hydromonitor; 7 – well; 8, 9, 11, 12 – pump; 10 – gravity separator; 13 – gas collecting dome; 14 – production platforms; flows: I – water-hydrate mineral pulp; II – gas hydrates depleted pulp; III – empty rock; I – gas released from the pulp as a result of gas hydrate dissociation; V – water gas hydrate mixture; VI – sea water; VII – working fluid for rock disintegration (sea water and pulp mixture)

– the impact on the productive stratum (starting with the well drilling) with the purpose of its disintegration by means of mechanical grinding at the minimum level of dissociation and gas hydrates recrystallization (due to the formation of local short-term zones under the non-equilibrium conditions) caused by submerged jets of high-pressure mixture of water and abrasive material (flow VII) using hydromonitor *6*. To increase the output volume, stems with hydromonitor nozzles are extended in the operating position, occupying the position perpendicular to the well's axis *7* and, turning around it, they are moving along up to the contact with the front of disintegration;

– formation, as a result of mixing the crushed hydrate-containing rock with water of the water-hydrate mineral pulp *2*;

– gravitational separating a part of rock mineral inclusions *3* of the relevant density and fractional composition from the water-hydrate mineral pulp *2* at some distance behind the active operating zone;

– withdrawal of the pre-enriched water-hydrate mineral pulp from the excavation site *1* through the pulp intake *5*, located behind the active operating zone, to the separator *10*, located at the seabed level;

– separation from the water-hydrate mineral pulp (flow I) (under the pressure higher than that of the hydrate formation equilibrium) in a gravity separator *10* of empty rock's part as a deposit, which is evacuated with the pump *11* to the bottom or through another well – to the discharged rock (flow III) and as a floating fraction: a mixture of water and free gas hydrates (flow V) (natural and partly recrystallized);

– feeding the separated gas hydrates in the mixture with water (flow V) which happens as the upper flow of the separator *10* by pump *12* onto the extractive platform *14*;

– selection of the part of the gas hydrates depleted water-hydrate mineral pulp (flow II), adding thereto sea water (flow VI) and supply (pump *8*) the resulting mixture (flow VII) under pressure to hydraulic jet gun *6* for rock disintegration (solid fraction of formed mixture acts as an abrasive);

– pumping out the rest of the depleted pulp (flow II) under the gas collecting dome *13* into the sea through a pipe, the open end of which is located above the upper limit of the gas hydrate stability (ULGHS). Meanwhile, as a result of being exposed to non-equilibrium conditions and the heat exchange with sea water, dissociation of the remaining gas hydrates into gas and water is taking place in the depleted pulp;

– sedimentation of the rocks onto the bottom (flow III), accumulation of gas in the gas collecting dome *13* and its supply to the platform *14*.

The suggested method for the hydrate deposit development suggests 4 basic stages:

1) hydrate containing rock disintegration in order to transfer it into the movable state;

2) concentrating pulp in the well as result of the rock cuttings sedimentation at a certain distance behind the active layer disintegration area;

3) separation (enrichment) of free gas hydrates in the gravitational separator and reducing the volume of pulp per the volume of water gas hydrate mixture and sedimentary rocks;

4) gas release as a result of the gas hydrate residues dissociation in the process of rock passing through the thickness of sea water at the interval exceeding the upper limit of this composition gas hydrate stability.

In this method of influence the gas hydrate layer is sublected to the impact:

– of sea water salts;

– of the heat energy released at partical transformation of the jet mechanical energy;

– of pulsations of pressure of the working mixture in the process of hydromonitor operation.

Thus gas hydrate for some time enters non-equilibrium conditions and partially dissociates. However, considering the heat balance of the process and features of kinetics, the impact will be short and will carry local character (in a contact zone of the working jet with the rock). As a result, dissociation of the certain part of gas hydrates is associated with rocks, will occur in one and free gas will forms hydrate in another place. In addition, the permanent presence of free gas will be the result of recrystallization of gas hydrates in zone of the destruction of rocks. The presence of compressible gaseous phase in the zone of pressure fluctuations also will be an additional factor of the impact on the layer.

Thus, the advantage of the proposed method of development of the gas hydrate deposit is as follows:

1) basic quantity of gas hydrates are extracted without the spending of energy on the a phase transition;

2) dissociation of the gas hydrates residue in the pulp for the extraction of gas is carried out due of low potential energy of sea water and changing of it pressure with depth.

2.3. Transportation of produced products

Regardless of the form of gas in the deposit (free gas or gas hydrates), the level of perfection of technical and technological solutions associated with operations involved in its preparation and transportation significantly influences the efficiency of the gas extraction technology. Nowadays natural gas is transported by sea pipelines in the gaseous state and by tankers in liquefied state (LNG-technology). However, in recent years, technology based on the ability of gas and water molecules to form gas hydrates, is actively developed. In the composition of gas hydrates, considerable volumes of gas can be stored for a long time at atmospheric pressure and a slightly negative temperature (Ovchynnikov, Ganushevych, & Sai, 2013). This technology has undeniable prospects for implementation in the near future, but it needs improvement and testing of its elements.

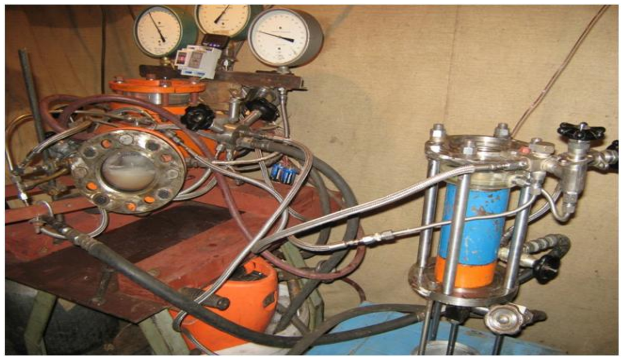
At present several concepts concerning transportation of gas in hydrate form are considered. The technology for transportation of non-equilibrium conditions (small negative temperature and atmospheric pressure) is the most attractive. It requires that gas hydrates be produced in the most stable form under these conditions (Ganushevych, Sai, & Korotkova, 2014). Currently, it is proposed to transport gas hydrate in the form of granules (Gudmundsson, 1996). However, over time granular hydrates tend to freeze into a monolyth which complicates unloading (Dawe, Thomas, & Kromah, 2003). Also granular gas hydrate only by 78% fills volume of vehicles or storages (Gudmundsson, Graff, & Kvaerner, 2003). Besides, much of the total surface area of the granules and system of open channels between channels granules stimulates the process of volumetric dissociation of the gas hydrate mass. Keeping them stable at atmospheric pressure needs additional costs for cooling to temperatures below a 258 K. Monolithic blocks of large size are a good option.

However, today the industrial technology of production does not exist (Yakushev, Gerasimov, Kwon, & Istomin, 2008). Due to thermal properties and features process of transportation and storage, gas hydrates is proposed to produce in the form of gas hydrate of blocks maximum cooled large, preserved with the layer of ice and refrigerated in the production process to the desired level (Pedchenko & Pedchenko, 2012).

This technology provides intensive production synthetic gas hydrates. Moreover it must have maximum gas content (up to 160 m^3/m^3). According to the research the formation of hydrates proposed to perform in the contact devices on the basis of jet devices (ejectors with elongated mixing chamber or jet devices with free jet). Their application allows increasing efficiency and simplify the process of technological design of technology (Pedchenko & Pedchenko, 2014) (Fig. 2).

Blocks will be formed from the previously cooled mixture of crushed and granulated hydrates of minimum porosity in the respective proportion. This solution allows to obtain blocks of uniform density and to waive the need them cooled (Fig. 3). To increase stability and the mechanical strength of hydrate blocks necessary force to preserve with the layer of ice.

(a)



(b)

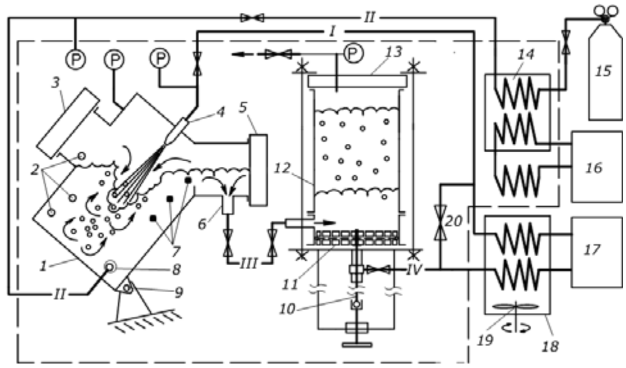


Figure 2. The laboratory unit for continuous production of gas hydrates: (a) photos; (b) scheme; 1 – reactor; 2 – temperature sensors; 3, 5, 13 – observation windows; 4 – inkjet apparatus; 6 – branch pipe; 7 – LEDs; 8 – bubbler; 9 – hinge; 10 – rod; 11 – plunger with filter; 12 – separator; 14, 18 – exchanger; 15 – balloon; 16 – refrigerator; 17 – pump; 19 – mixer; 20 – valve; jets: I, IV – water; II – gas; III – mixture of hydrate and water

For this purpose, on their surface freeze crust 1 – 2 mm is sufficient (ice crust, formed as result self-preservation is thinner) (Gudmundsson & Parlaktuna, 1991). In the study of the force preservation of the gas hydrate blocks the need re-application of water from endurance to crystallization of the previous layer was established. In the first application main part of the pores was blocked and "cementing" of the surface of the sample to a depth of water penetration. In the second – pores are blocked completely, surface defects are smoothed and ice layer are frozen (Fig. 4).

Consequently, the existence of the sample in equilibrium conditions (for example, as a result of application of water) thickness of the ice crust is determined by the balance of energy and amount of water in its pores and on the surface. Thus, forced preservation allows you to create for of gas hydrate under a layer of ice conditions its stability while the sample itself may be in equilibrium conditions.

The method of gas hydrate production in the form of blocks with internal energy source, i.e. preserved layer of ice, is proposed, considering the properties of gas hydrate and experimental results (Fig. 5, 6).

(a) (b) (c)

Figure 3. Transverse section of the gas hydrate block after the formation

(a) (b) (c)

Figure 4. Forced conservation of sample of gas hydrates with the ice layer: (a) application of water; (b) gloss of a layer of ice on a sample; (c) ice layer on a section of a sample

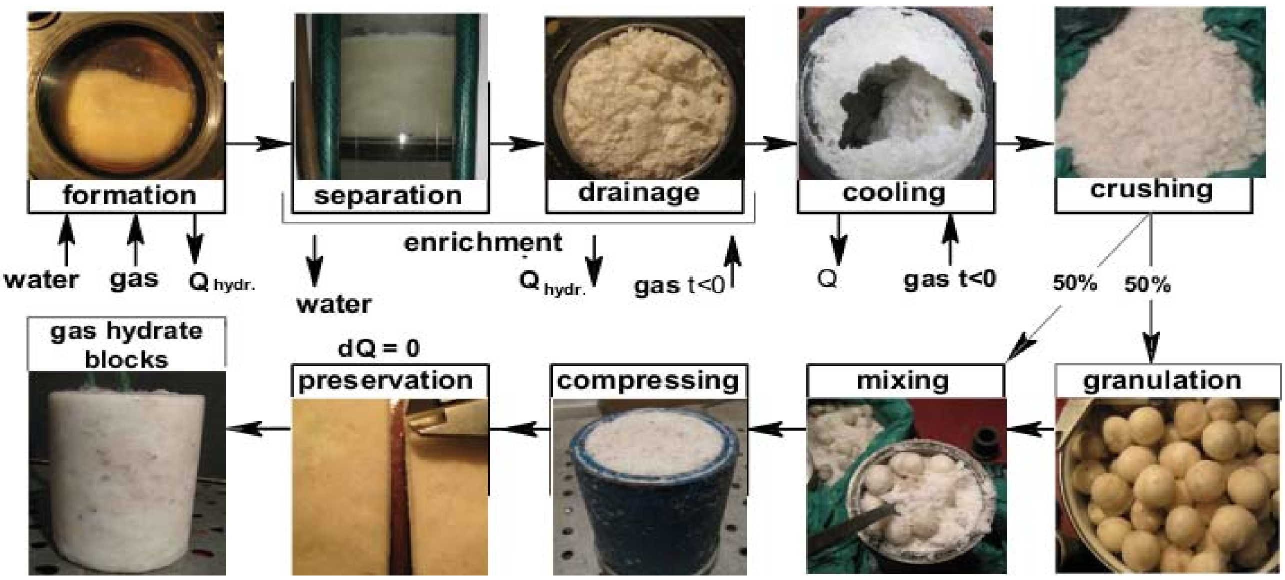


Figure 5. Scheme for the method of gas hydrate blocks production

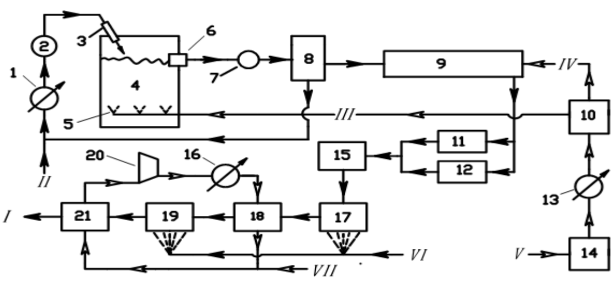


Figure 6. Method of gas hydrate blocks production: 1 – cooling of water; 2 – water pumping; 3 – feed water jet into the reactor; 4 – formation of gas hydrates; 5 – bubbling gas; 6 – selection of gas hydrates; 7 – vibration treatment; 8 – separation; 9 – concentration and cooling; 10 – hydrate crushing; 11 – hydrate granulation; 12 – gas separation; 13 – gas cooling; 14 – gas preparation; 15 – formation of blocks; 16 – air cooling; 17 – the first water supply to the blocks; 19 – the second water supply to the blocks; 18 – cementing surface; 21 – freezing of the ice layer; 20 – air circulation; jet: I – blocks; II, VI – water; III – methane; IV – condensate; V – gas; VII – air

It includes: gas hydrate production with a significant water content, its separation, enrichment of the gas hydrate mass by transferring the residue water (intercrystalline and captured) to the composition of the hydrate and increasing the level of filling the crystal lattice with gas molecules, single cooling of gas hydrate $(T \leq 258\ \text{K})$, granulating of one part of the gas hydrate and crushing of another, formation of blocks from their mixtures, their forced conservation by the layer of ice.

For realization of this method, a project pilot plant with a capacity of 20 thousand gas m^3/day (140 tons per day hydrate) is developed (Fig. 7). The pilot plant is designed for production of gas hydrate blocks with the weight up to 250 kg. Gas consumption for technological needs of the pilot plant during the summer installation is 2400 m^3/day (or 12% of its capacity). At lower temperatures the gas consumption is reduced to 568 m^3 day (or 2.8%).

Thus the gas hydrate blocks manufactured in accordance with the proposed technology (Pedchenko & Pedchenko, 2012) can be regarded as "devices" for concentration of gas with an internal energy source. They are suitable for long-term storage and transportation at atmospheric pressure and a slightly negative temperature.

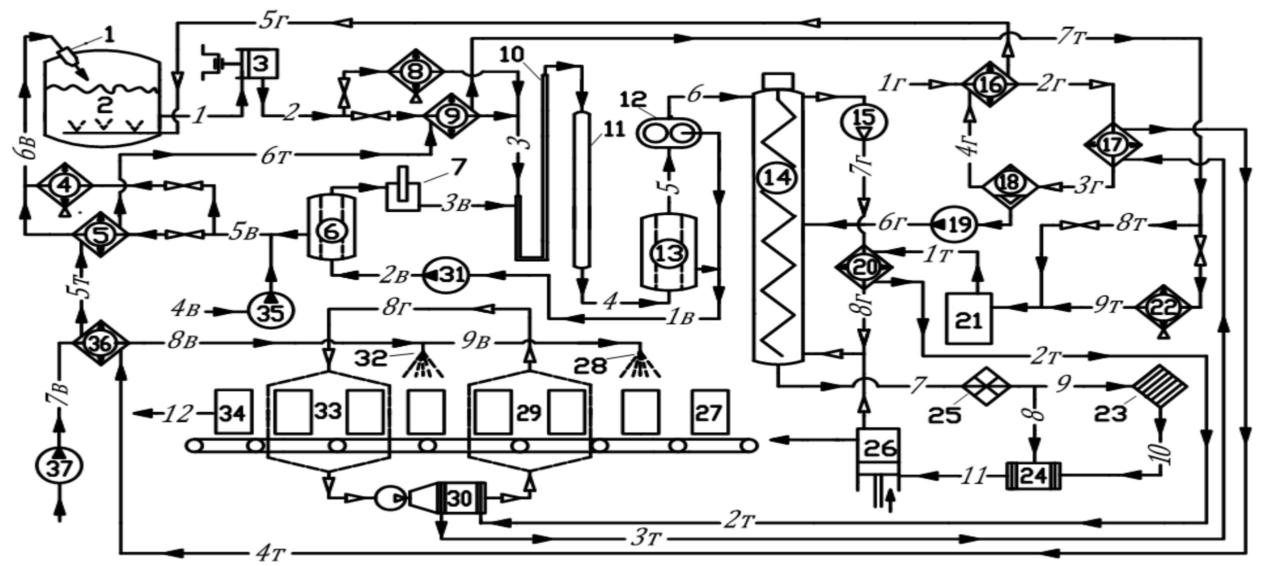


Figure 7. Principle scheme of the installation for the production of hydrocarbon gas hydrate in the form of blocks with the capacity of 140 t/day (20 thousand m^3/day of gas): 1 – jet apparatus; 2 – reactor; 3, 7, 19, 31, 35, 37 – pump; 4, 8, 22, 30 – device of air cooling; 5, 9, 16, 17, 20 – heat exchanger; 6, 13.18 – separator; 10 – coiled pipe; 11 – moderator; 12 – squeezing device; 14 – column of gas hydrates drying; 15 – compressor; 21 – refrigerator; 23 – granulator; 24 – mixer; 25 – straw chopper;26 – press for the formation of gas hydrate blocks; 27, 34 – gas hydrate blocks; 28, 32 – nozzle; 29, 33 – zone of blowing gas hydrate blocks; jets: 1 – 4 – mixture of gas hydrate and water; 5, 6 – crude gas hydrate mass; 7 – drained and cooled gas hydrates; 8, 9 – crushed hydrates; 10 – granular hydrates; 11 – mixture of crushed and granulated gas hydrates; 12 – gas hydrate blocks; 1Г – 3Г – raw gas; 4Г, 5Г – dry gas; 6Г – condensate; 7Г, 8Г – gas of drying; 1В – 9В – water, 1Т – 9Т – cold carrier

Deleting from the main part of deposit of the products in the form of gas hydrate in conjunction with the technology transport and storage of gas in hydrate form will significantly reduce the specific consumption and increase the competitiveness of the project.

2.4. The method of developing (a compatible or separate) offshore fields of gas or gas hydrates

Nowadays, natural gas is transported by pipelines and LNG-tankers. However, such transport technology, based on significant investments, will be effective at presence of significant gas resources confirmed for this field (Seungyong, 2001). In many cases the traditional technologies of gas transportation can not fully meet the demands of projects related to the development of marine fields.

In their article, Gudmundsson & Borrehaug (1996) showed, that capital costs on a technological chain of the NGH-technologies for transporting 4 billion m^3 of natural gas at a distance of 5.5 thousand km were lower by

26% compared to LNG-technology. Application of NGH-technologies will be economically more feasible, starting from a distance of 1000 km, while for LNG-technologies this distance should be greater than 3000 km (Gudmundsson, Graff, & Kvaerner, 2003).

Gas hydrates can at relatively low pressures concentrate large volumes of gas (up to 160 volumes of natural gas per one volume of hydrate). But this figure is almost four times smaller compared to liquefied natural gas. Considering the hydrate density, the specific contents of natural gas and rather mild thermo-baric conditions of storage, NGH-tankers can be built at least twice as big as LNG-analogues and can transport 250 thousand m^3 of cargo (Gudmundsson & Borrehaug, 1996). Factories producing gas hydrates do not need special or unique equipment in contrast to the factories for natural gas liquefaction, which greatly reduces the cost of NGH-technology (Kanda, 2006). In addition, the power of lines for the production of gas hydrate may be 4 times lower than of line for LNG production, without increase in its cost. This gives an opportunity to smoothly adjust the production in case of changing demand in natural gas (Gudmundsson, Parlactuna, & Khokhar, 1994).

Proceeding from considerations listed above, the method of developing (compatibly or separately) marine gas and gas hydrate fields (Fig. 8) is proposed.

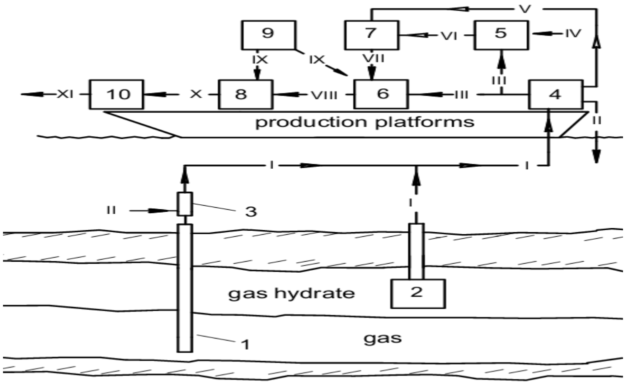


Figure 8. Method of development (a compatible or separate) of the offshore fields of gas or gas hydrates: 1 – extraction of gas; 2 – extraction of gas hydrates; 3 – formation of a mixture of gas hydrates, gas and water; 4 – separation of the mixture of gas hydrates, water and gas on the gas, water (the gravitational) and the mixture that consists of gas hydrates, a film water and water captured between the crystals; 5 – melting in the limited volume of party of the gas hydrates to obtain of gas jet of high pressure; 6 – draining of a mixture of gas hydrates, film and captured between crystals water by binding of remains of water in hydrates; 7 – compression in the jet compressor of gas jet, separated from the mixture due to the energy of jet gas of high pressure; 8 – a single cooling of gas hydrate mass; 9 – production of cold; 10 – formation of gas hydrate blocks and their preservation with the ice layer; jets: I – a mixture of gas hydrates, water and gas; II – water; III – mixture of gas hydrates, a film water and water captured between crystals; IV – supply of heat; V – gas of low pressure; VI – gas of high pressure; VII – gas of average pressure; VIII – gas hydrates; IX – the coolant

It provides:

– uncovering of productive layers by wells;

– impact on the layer in order to extract gas or gas hydrates;

– binding of the extracted gas in gas hydrate;

– supply of gas hydrates mixture, water and gas to the extractive platform. During the development of gas hydrate deposits, this mixture is formed from extracted gas hydrates, water, used for the destruction of rocks, and the gas released from the hydrate as a result of dissociation to create the effect of gas-lift in the pipeline. During the development of gas deposits, the mixture is formed as a result of contact between natural gas and sea water accompanying the removal of the process heat through the walls of the pipeline on the site with thermo-baric conditions of the hydrate formation;

– separation of the mixture into gas, gravitational water and mixture, composed of gas hydrate, film water and water captured between crystals;

– melting in the limited volume of the gas hydrate part for receiving gas of high pressure for its further use in machineless compression (Makogon, 2001);

– compression of the low pressure gas separated from the mixture in the jet compressor due to the energy of the high pressure gas jet;

– drying (concentration) of gas hydrates and water (film and captured between the crystals) mixture by its binding in the hydrate during its contact with the (cooled) jet of gas at the average pressure and removal of the process heat;

– one-time cooling of the obtained gas hydrate mass, taking into account the heat balance of the further technological operations and processes up to the moment of gas consumption;

– formation of the prepared gas hydrate in blocks and its preservation within the ice layer;

– transportation and storage of gas hydrate blocks in terrestrial storages at atmospheric pressure and the temperature lower than 278 K.

2.5. Storing gas in hydrate form

The possibility of natural gas storage in the form of gas hydrate, organization of terrestrial storages of gas hydrates near large gas consumers of (Fig. 9) (Pedchenko & Pedchenko, 2013) is another promising field of gas hydrate technology use. Building of such storages could significantly smooth out seasonal fluctuations in gas production and represent an alternative to the construction of underground gas storage facilities. Moreover, these storages and technologies of their exploitation can best supplement the technological chain of production, transportation and storage of natural gas of the marine deposits.

To increase the effectiveness of the proposed technology, hydrate blocks must be stored under a layer of polyurethane (thickness of 0.5 – 0.7 m) in terrestrial inflatable structures covered with double-layer of soft shell with nonflammable gas locking layer. These structures are in fact constructions lying on the gas cushion with pressure above atmospheric only to maintain the shell (Fig. 9). We propose to place such storages near gas consumers. This will allow to supply gas to distribution networks of low pressure. Therefore hydrates are dissociated at a pressure of 0.3 – 0.4 MPa, and hence at a much lower temperature (coolant temperature to melt the hydrate will not exceed 283 K).

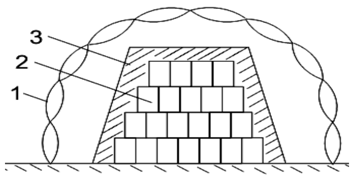


Figure 9. Scheme of gas hydrate storage: 1 – elastic double-layer shell; 2 – hydrate blocks; 3 – layer of polyurethane

Calculation of parameters of the gas hydrates storage (2800 tons) in the terrestrial inflatable structures is given in Table 1 and Figure 10 – the dynamics of temperature change on the hydrate surface.

Table 1. Parameters of gas hydrate storage in above-ground vaults

The thermodynamic parameters	January	July
Thermal resistance, (m^2·K)/W:		
– transition heat, R_α	0.230	0.090
– coating of the layer of PVC, R_{pvc}	0.025	0.025
– locking layer, R_{loc}	0.220	0.180
– covering (no layer of polyuret.), R_{cov}	0.340	0.280
– covering (with a layer of polyuret.), R_{pu}	17.000	16.600
The heat flow to the hydrates, W/m^2:		
– without insulation polyurethane, q	20.58	104.1
– insulated with polyurethane, q_{pu}	0.64	92.4
The heat flow in the Inflatable structures to of gas hydrates, kW		
– without insulation polyurethane Q_{ext}	80.77	409.0
– insulated with polyurethane, $Q_{ext^{\cdot}pu}$	2.53	9.36
The heat flow from the earth, Q_{ear}, kW	9.0	9.0
Energy consumption for cooling, Q_{cool}, kW	6.6	15.3

Costs of gas hydrate blocks storage during the year in above-ground vaults will amount in terms of gas equivalent to 15.86 thousand. m^3, which is only 0.3% of the storage capacity.

In gas hydrate production, about 80% of energy is consumed by recycling heat from the process. Before the gas consumption, the same amount of energy is consumed by hydrate melting.

To improve efficiency of the technologies, dissociation of gas hydrate blocks in the summer must be carried out by solar energy.

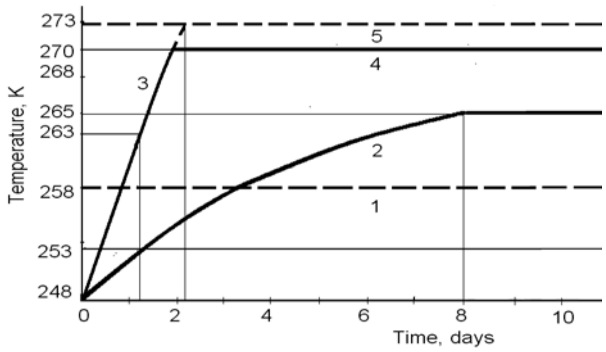


Figure 10. Dynamics of gas hydrate surface temperature change in above-ground vaults: limit of hydrate stability 1 – without mothballing; 2 – winter without additional cooling; 3 – summer without additional cooling; 4 – summer with additional cooling; 5 – laid up with the layer of ice

2.6. Technological complex for production, transportation and storage of gas from the offshore fields of gas or gas hydrates

The proposed technological chain (Fig. 11) involves:

– extraction of products from deposits (hydrate and/or gas) mainly in the form of moistened gas hydrates and partly – free gas, binding this gas and the remaining water in the gas hydrate;

– production of gas hydrate in the form of gas hydrate blocks, its transportation without additional cooling, storage in above-ground vaults at the temperature of 270 K, hydrate melting by solar energy.

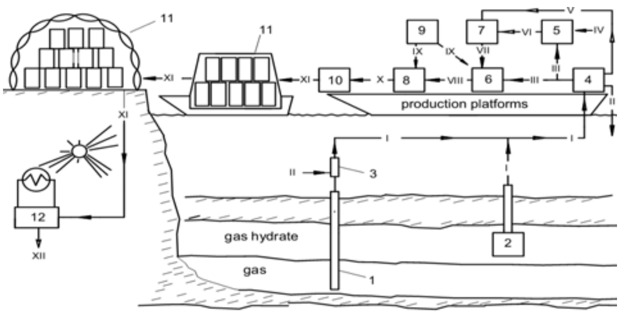


Figure 11. Technological complex for production, transportation and storage of gas from the offshore gas or gas hydrate fields: 1 – extraction of gas; 2 – extraction of gas hydrates; 3 – formation of gas hydrates, gas and water mixture; 4 – separation of gas hydrates, gas and water mixture into gas, water (gravitational) and the mixture that consists of gas hydrate, film water and water captured between the crystals; 5 – melting in the limited volume of the gas hydrates part to obtain hig- pressure gas flow; 6 – drying the mixture of gas hydrates, film water and the water captured between crystals by binding the remaining water in hydrates; 7 – compression in the jet compressor of gas flow, separated from the mixture due to the energy of high pressure gasflow; 8 – single cooling of gas hydrate mass; 9 – production of cold; 10 – formation of gas hydrate blocks and their preservation with the ice layer; 11 – transportation and storage of gas hydrate blocks; 12 – dissociation of gas hydrates due to solar energy; flows: I – mixture of gas hydrates, water and gas; II – water; III – mixture of gas hydrates, film water and water captured between crystals; IV – heat supply; V – low pressure gas; VI – high pressure gas; VII – gas of average pressure; VIII – gas hydrates; IX –coolant; X – cooled gas hydrate; XI – hydrate blocks, laid up with the ice layer; XII – gas for consumption

3. CONCLUSIONS

1. The proposed method of extraction and transportation of natural gas from the offshore fields of gas or gas hydrate results in technical solutions which allow to achieve the maximum reduction of energy consumption due to the complex consideration of thermal properties and parameters of the system components interaction within the deposit under development.

2. The main idea of the proposed method of gas hydrate deposits development is extracting the maximum amount of gas hydrates from the productive stratum without spending energy on the phase transition. Given the gas hydrate physical properties, dissociation of its

residue is carried out due to the sea water low energy and changing of its pressure with depth.

3. The proposed gas hydrate technology creates important preconditions for the development of small and medium-sized remote gas fields (including gas-hydrate fields), creating a network of above-ground hydrate storage vaults. It also helps to improve the efficiency and competitiveness of marine technologies of natural gas transportation in hydrate form.

4. The use of alternative energy sources (natural cold and solar energy) for production and dissociation of gas hydrate in above-ground hydrate storage vaults allows to considerably reduce capital and energy costs associated with the technological chain of hydrocarbon gases transportation and storage in hydrate form.

5. The existing technologies for survey, exploration, drilling and production of hydrocarbon energy resources can be successfully used for the development of gas hydrate deposits on condition of their slight upgrading. Implementation of gas hydrate technologies allows to refuse from more complex and expensive systems of preparation, transportation and storage of the extracted products.

6. The reviewed works on the borehole hydro-mining are unprecedented in the world by type of the extracted ores and the parameters of hydro-destruction. Furthermore, the parameters of the used hydraulic equipment in the borehole hydro-mining in connection with the specifics of this method of extraction also do not have analogues among the known hydraulic systems. Therefore testing of the proposed method for development of gas hydrate deposits requires substantiation by a series of experimental studies.

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ABSTRACT (IN UKRAINIAN)

Мета. Обґрунтування і розробка принципових схем, прийнятних для існуючого рівня техніки, способів видобування й транспортування природного газу, газових або газогідратних морських родовищ, та підвищення їх ефективності шляхом максимального зниження енерговитрат у результаті комплексного урахування теплофізичних властивостей і параметрів взаємодії складових системи у межах покладу, що розробляється.

Методика. Аналіз та узагальнення результатів комплексу експериментальних досліджень, проведених на багатофункціональній лабораторній газогідратній установці.

Результати. Запропоновано технологію вилучення газогідрату із продуктивного пласта без витрати енергії на фазовий перехід. Обґрунтовано доцільність сумісної розробки газогідратних і газових родовищ шляхом зв'язування вільного газу в газогідрат за рахунок наявності необхідних термобаричних умов при його проходженні крізь морську товщу. Обґрунтовано доцільність поєднання в один ланцюг запропонованої технології розробки морських газогідратних і газових родовищ з технологіями транспортування газу у газогідратній формі та його зберігання у наземних сховищах.

Наукова новизна. Обґрунтовано можливість вилучення газогідрату із продуктивного пласта без витрати енергії на дисоціацію шляхом створення умов його перекристалізації у результаті сумісної дії затоплених струменів морської води у суміші з абразивним матеріалом та пульсацій тиску.

Практична значимість. Запропонована газогідратна технологія створює важливі передумови розробки малих та середніх віддалених родовищ газу (у тому числі й газогідратних), створення мережі наземних гідратосховищ, підвищення ефективності та конкурентоздатності технології морського транспортування природного газу у газогідратній формі.

Ключові слова: *газові гідрати, природний газ, газогідратний пласт, дисоціація, збагачення, фазовий перехід, газогідратні блоки*

ABSTRACT (IN RUSSIAN)

Цель. Обоснование и разработка принципиальных схем, приемлемых для существующего уровня техники, способов добычи и транспортировки природного газа, газовых или газогидратных морских месторождений и повышение их эффективности путем максимального снижения энергозатрат в результате комплексного учета теплофизических свойств и параметров взаимодействия элементов системы в пределах разрабатываемой залежи.

Методика. Анализ и обобщение результатов комплекса экспериментальных исследований, выполненных на многофункциональной лабораторной газогидратной установке.

Результаты. Предложена технология извлечения газогидрата из продуктивного пласта без затрат энергии на фазовый переход. Обоснованно целесообразность совместной разработки газогидратных и газовых месторождений путем связывания свободного газа в газогидрат за счет наличия необходимых термобарических условий при его прохождении сквозь морскую толщу. Обоснованно целесообразность объединения в одну цепь предложенной технологии разработки морских газогидратных и газовых месторождений с технологиями транспортировки газа в газогидратной форме и его хранения в наземных хранилищах.

Научная новизна. Обоснована возможность извлечения газогидрата из продуктивного пласта без затрат энергии на диссоциацию путем создания условий его перекристаллизации в результате совместного воздействия затопленных струй морской воды в смеси с абразивным материалом и пульсаций давления.

Практическая значимость. Предложенная газогидратная технология создает важные предпосылки разработки малых и средних отдаленных месторождений газа (в том числе и газогидратных), создания сети наземных гидратохранилищ, повышения эффективности и конкурентоспособности технологии морской транспортировки природного газа в газогидратной форме.

Ключевые слова: *газовые гидраты, природный газ, газогидратный пласт, диссоциация, обогащение, фазовый переход, газогидратные блоки*

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