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TECHNOLOGY FOR DEVELOPMENT OF METHANE-HYDRATE DEPOSITS JOINTLY WITH RECEIVING FRESH WATER

1. INTRODUCTION

Natural gas-hydrates are crystalline structures of the clathrate type, in which gas molecules are incorporated into an ice-like framework of water molecules [1–3].

There are three main methods for extracting gas of gas-hydrate, the most prepared for practical implementation is: the first one – pumping pressure of warm water into the well; 2nd – depressive; 3-rd – through which carbon dioxide gas is injected into the gas-hydrate stratum to replace the methane gas. At the heart of technologies using these methods is the general principle: the impact on the formation, resulting in the loss of thermodynamic stability of the gas-hydrate and its decomposition into methane and fresh water. To improve the efficiency of gas-hydrate gas production, it is preliminary advisable to perform hydraulic fracturing of the formation [3, 4].

The article considers the technology of methane-hydrate deposits development, which allows receiving fresh water along with methane gas as an additional product. The main attention is paid to the technology of development of methane-hydrate deposits in conjunction with the production of fresh water according to the method by which carbon dioxide is injected into the gas-hydrate formation to replace the methane gas.

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2. SCHEMES AND PRINCIPLE OF EFFECT OF INSTALLATIONS FOR GAS PRODUCTION FROM METHANE-HYDRATE DEPOSITS AND JOINT RECOVERY OF FRESH WATER

Authors presented three metods for gas extraction from methane-hydrates deposits. There are following:

- method of gas extraction from gas-hydrates by pumping of warm water,
- method of gas extraction from gas-hydrates by lowering the pressure
- method of gas extraction from gas-hydrates by carbon dioxide injection to hydates deposits

2.1. Method of gas extraction from gas-hydrates by pumping of warm water

Diagram of the plant for gas extraction from methane-hydrate deposits and joint production of fresh water by pumping warm water from the sea surface into the gas--hydrate reservoir through the injection well and pumping out the decomposition products of hydrates-gas-methane and water from a pumping well located at some distance from the injection well is shown in Figure 1.

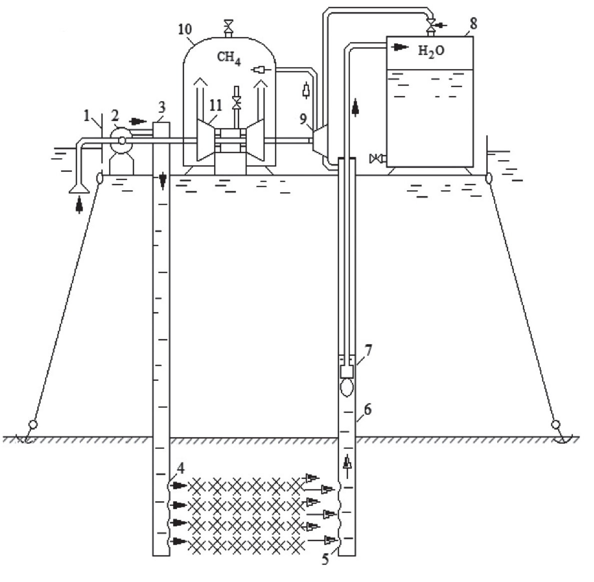

Fig. 1. Schematic diagram of the plant for gas and fresh water extraction by the method of thermal action on the gas-hydrate layer. 1 – a platform for placing equipment of the installation; 2 – pump for supplying warm water from the sea surface to the bottom of the pressure well; 3 – pressure well; 4 – windows for the removal of warm water into the bottom of the pressure well; 5 – windows for the removal of the gas-water suspension from the formation into the pumping well; 6 – pumping well; 7 – submersible electric pump; 8 – fresh water tank; 9 – the compressor; 10 – gasholder; 11 – gas turbine drive

The installation works as follows. Warm water from the sea surface is fed by pump 2 to the pressure well 3 to enter it into the face of the hydrate formation through the windows 4. As a result of heating methane-hydrates in the pores of the ground, these hydrates decompose into methane gas and fresh water. Under the influence of the pressure difference between the pressure head and the evacuation well, the gas-water mixture moves along the pore space of the hydrate formation to the windows 5 and enters the pumping well 6. The submersible electric pump 7 picks up the water from the pumping well 6 and sends it to the fresh water tank 8. In this case, the compressor 9 pumps the gas from the upper gas cavity of the pumping well and sends it to the gas holder 10. For driving the pump 2 and the compressor 9, a gas turbine unit 11 is used and consumes part of the produced gas as fuel.

2.2. Method of gas extraction from gas-hydrates by lowering the pressure

Schematic diagram of the plant for gas extraction from methane-hydrate deposits and joint production of fresh water by lowering the pressure in the gas-hydrate formation is shown in Figure 2. When the pressure is lowered, the gas-hydrates decompose, and the released methane and fresh water are removed from the pumping wells located at a certain distance from each other.

The installation works as follows. From the formation 4 through the windows for the intake of the gas-water suspension 5 and through the well 6 the water is pumped by the submersible electric pump 7 and directed to the fresh water tank 8. Meanwhile, the methane gas bubbling through the water into the upper part of the well is pumped out by the compressor 9 to the gas holder 10. The required depression in the hydrated reservoir is achieved by pumping water from the well with a decrease in the water level in the well to a mark corresponding to the required depression. To drive compressors 9, pumps 2 and 7, a gas turbine unit 11 is used, which uses a part of the produced gas as fuel. Lowering the temperature of the gas-hydrate formation Δt_{ref} as a result of heat absorption Q during the decomposition of gas-hydrates can be determined from the following equation of heat balance for a single volume of the gas-hydrate formation V:

$$\Delta t_{ref} = \frac{Q}{V\left[m \cdot S_{gg} \cdot \rho_{gg} \cdot c_{gg} + m \cdot S_v \cdot \rho_v \cdot c_v + m \cdot S_g \cdot \rho_g \cdot c_g + (1-m) \cdot \rho_s \cdot c_s\right]} \quad (1)$$

where:

S_{gg}, S_v, S_g – pore saturation with gas-hydrates, water and gas,

m – porosity of the hydronetasated layer,

ρ_{gg}, ρ_v, ρ_g, ρ_s – density of gas-hydrates, water, gas and soil,

c_{gg}, c_v, c_g, c_s – heat capacity of gas-hydrates, water, gas and soil.

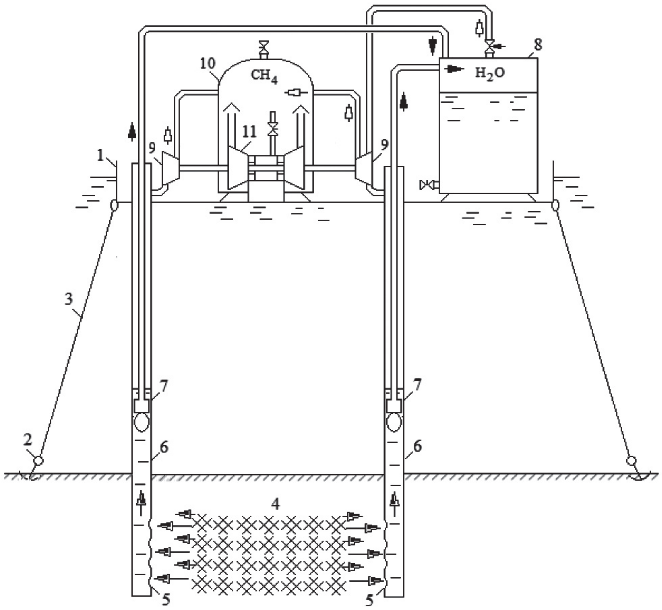

Fig. 2. Schematic diagram of the plant for the extraction of methane gas and fresh water from the gas-hydrate deposit by lowering the pressure (decompression). 1 – a platform for placing equipment of the installation; 2 – anchor; 3 – ropes; 4 – gas-hydrate layer; 5 – windows for the removal of the gas-water suspension from the formation into the pumping well; 6 – pumping well; 7 – submersible electric pump; 8 – fresh water tank; 9 – the compressor; 10 – gasholder; 11 – gas turbine drive

Calculation by formula (1) at $m = 0.25$ and $S_{gg} = 0.2$ gives a decrease in the temperature of the gas-hydrate formation equal to $\Delta t_{ref} = 10°C$, which determines the need to supply the gas-hydrate formation with an appropriate amount of heat to prevent the freezing process and blockage of the formation by ice.

2.3. Method of gas extraction from gas-hydrates by carbon dioxide injection to hydates deposits

The most promising method of gas extraction from gas-hydrates is the development of methane-hydrate deposits in conjunction with the production of fresh water, according to which carbon dioxide is injected into the gas-hydrate stratum to replace methane.

The extraction of methane by introduction into the gas-hydrate layer of CO_2 is based on different values of the equilibrium thermodynamic parameters of methane-hydrate and CO_2-hydrate: at the same pressures, the equilibrium temperature of CO_2-hydrates is much higher than the hydrates of CH_4 [2, 3]. In the presence of CO_2, the composition of the gaseous atmosphere changes, which disrupts the equilibrium state of methane hydrate at these thermobaric parameters and, on the one hand, leads to a loss of its thermodynamic stability, and on the other, to the formation of CO_2-hydrates. The decomposition conditions of methane-hydrate during injection into the CO_2 system are determined, along with pressure and temperature, the composition of the gas mixture, the hydrate number of the mixed hydrate formed from this mixture, the heat of its formation. An important role is played also by the kinetics of the substitution process and the development of the gas-hydrate contact surface, the presence of free water and a number of thermodynamic factors listed above.

This technology has the following additional advantages:

1) the disposal of CO_2, which is a greenhouse gas,
2) the resulting hydrates of CO_2 ensure the integrity of the pore space of the hydrate-containing deposit.

When developing the methane-hydrate mining technology together with the production of fresh water by using the method of methane replacement in hydrates with carbon dioxide, the results of the experimental studies given in [5] were taken into account. According to these results, the degree of substitution for these thermobaric conditions depends mainly on the concentration of CO_2 in the gas mixture in equilibrium with the hydrate and thus has no limitations when continuously pumped through a sample of methane-hydrate.

In Figure 3 there is a schematic diagram of an installation for the development of methane-hydrate deposits in this manner.

The installation works as follows. Carbon dioxide gas from the gas holder 10 is introduced into the slaughter through the well windows 1 and through the windows 2, the gas--water slurry is pumped out by the submersible electric pump 5 to the separator 6 to separate the gas phase consisting of a mixture of CH_4 and CO_2 from water. From the separator, water is taken to a fresh water tank 12 and a gas mixture of methane and carbon dioxide is passed through a water absorber 7, where carbon dioxide is absorbed by water and methane bubbles through the water and is sent to the methane gas generator 9. Water with dissolved CO_2 is passed through a hydraulic turbine 16 and sent to a desorber 8 where the carbon dioxide is degassed from the water due to the pressure reduction and is directed to the downhole through the windows 1 by the compressor 13. At the same time, the water from the desorber is recirculated to the absorber 7 by the pump 15.

Carbon dioxide of recirculation (with a multiplicity factor of recirculation, for example, $Kp = 5$) having a relatively high temperature after compression in compressor 13 is sent together with carbon dioxide from gasholder 10 through the well into the bottom, which results in the melting of the nearby part of the methane hydrates in the formation and the outlet of fresh water and methane gas. As it moves along the pores of the reservoir, CO_2 cools and replaces methane in the hydrates of the main part of the formation.

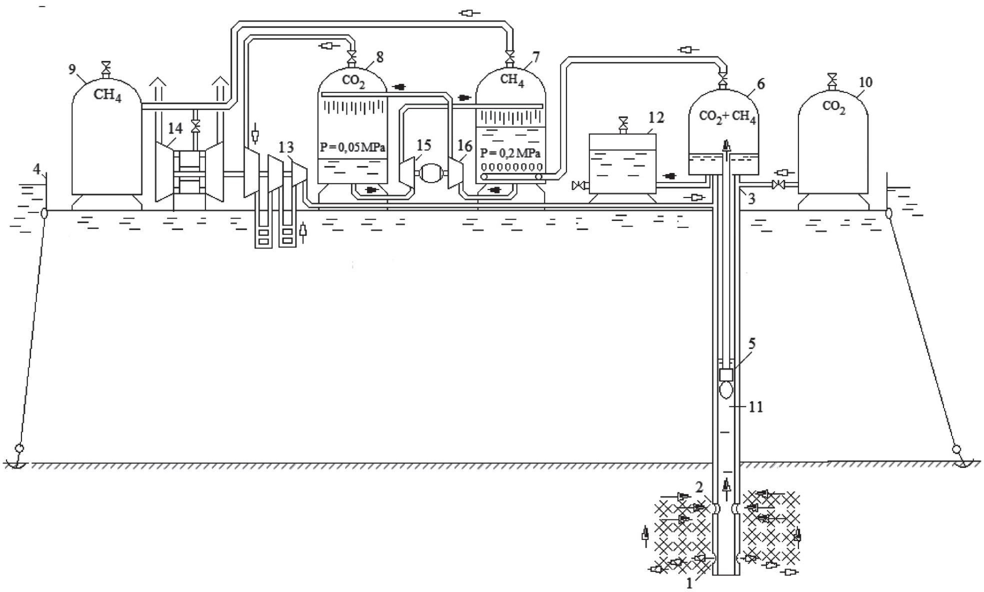

Fig. 3. Schematic diagram of the plant for extracting gas and fresh water from the gas-hydrate deposit by injecting carbon dioxide into the formation. 1 – window for supplying carbon dioxide to the gas-hydrate layer; 2 – window for receiving a suspension of methane gas and fresh water from the gas-hydrate formation; 3 – a window for entering carbon dioxide into the annular space of the well; 4 – platform; 5 – electric pump; 6 – gas separator from water; 7, 8 – respectively absorber and desorber of carbon dioxide; 9, 10 – respectively, gasholders of gas-methane and carbon dioxide; 11 – a pipe for lifting a suspension of methane and fresh water; 12 – fresh water tank; 13, 14 – respectively compressors for the compression of carbon dioxide and methane, located on a single shaft with a gas turbine drive; 15, 16 – pumps for water recirculation and hydraulic turbine

This results in the release of methane gas and the conservation of carbon dioxide gas from the gas holder 10 in the hydrate formation. At the same time, a gas-water suspension is evacuated from the well by the submersible electric pump 5 to the separator 6, where the gas phase consisting of a mixture of CH_4 and CO_2 that is not included in the hydrate is separated from the water.

It should be noted that with the increase in the rate of CO_2 recirculation, the fresh water output will increase proportionally, but the energy consumption in the methane--hydrate deposit development plant will also increase.

In Figure 4 schematic diagrams of the processes of hydrate decomposition for the above 3 methods are shown.

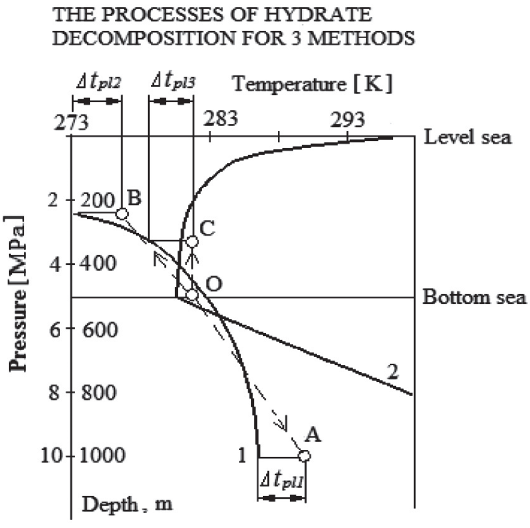

Fig. 4. Schematic images of the processes of decomposition of hydrates. 1 – equilibrium hydrate formation curve for the water-methane system [1, 3]; 2 – water temperature in the depth of the sea [1, 3]; line OA is the process of decomposition of hydrates according to the 1st method; line OB – the process of decomposition of hydrates according to the 2nd method; line OC – process of decomposition of hydrates according to the third method; Δt_{pl1}, Δt_{pl2}, Δt_{pl3} – temperature head when melting methane hydrates, respectively, for the 1st, 2nd and 3rd methods.

3. ESTIMATION OF ENERGY AND ECONOMIC EFFICIENCY OF DEVELOPMENT OF METHANE-HYDRATE DEPOSITS JOINTLY WITH RECEIVING FRESH WATER

To evaluate the energy efficiency of gas-producing dual-purpose plants, it is advisable to apply a methodology based on the use of specific energy indicators. Determine such indicators can be found from the formulas and relationships given for gas-hydrate process units in [6, 7].

Calculations of specific energy parameters were carried out for the development of a single volume of the gas-hydrate deposit (V = 1 m^3) with a production rate of gas-methane Q_g = 1 m^3/h with the following data taken into account works [1–3, 8, 9]:

$\mu_1 = 1{,}3 \cdot 10^{-3}$ Pa·s – coefficient of dynamic viscosity of warm water;
$k_1 = 10^{-14}$m^2 – coefficient of formation permeability with gas-hydrates;
$\mu_2 = 1{,}1 \cdot 10^{-5}$ Pa·s – coefficient of dynamic viscosity of gas-methane;
$k_2 = 10^{-12}$ m^2 – coefficient of formation permeability without gas-hydrates;
F_1 = 1 m^2 – cross-sectional area of a unit volume of a hydrate formation;
m = 0,25 – porosity of the hydronetasated layer;
H = 500 m – depth of face (Fig. 4);
$K_ð$ = 5 – coefficient of recirculation rate CO_2.

Preliminary calculations of the useful and expended exergy of gas-producing dual--purpose plants show that the numerical values of exergy of fresh water and the heat of gas-hydrates melting are less than 1% of the numerical value of the chemical exergy of methane gas. Therefore, in practical calculations, a simplified expression can be used to determine exergy efficiency:

$$\eta_{ex} = \frac{e_g - L_m / \eta_k}{e_{gg}} \tag{2}$$

where:

$e_g = 0{,}95 \cdot Q_h$ – chemical exergy of methane gas,

Q_h = 50 040 KJ/kg methane – the lowest heat of combustion of gas-methane,

L_m / η_k – chemical exergy of gas-methane spent on driving pumps and compressors,

L_m – useful work of a heat power plant for driving pumps and compressors,

η_k – efficiency of a direct Carnot cycle for a heat-power plant (we accept $\eta_k = 0{,}4$) [10],

$e_{gg} = e_g$ – exergy of methane hydrate (excluding exergy of fresh water and heat of melting of methane hydrates).

Table 1 shows the results of calculations of the specific production rate of wells for fresh water, specific energy consumption and exergy efficiency for gas-producing dual-purpose units operating in the three ways described above.

Table 1

Results of calculations of specific production rate of wells for fresh water, specific energy consumption and exergic efficiency for gas-producing dual-purpose plants

n/n	Determined values	Method of gas hydrate deposit development		
		1	2	3
1	Fresh water production rate, G_w (kg/h)	4.5	4.5	0.5
2	Energy consumption for pump and compressor drive, L_m (KWh)	3.2	2.5	0.4
3	Exergy efficiency, η_{ex}	0.13	0.42	0.45

Analysis of the performed calculations shows that the lowest energy costs, and the exergy efficiency is the largest, a two-purpose facility operating on the basis of methane replacement in CO_2 hydrates, but the fresh water discharge in this facility is less than ten times that of the other two.

Estimation of the economic efficiency of the development of methane-hydrate deposits in conjunction with the production of fresh water

The industrial development of gas-hydrate deposits is currently not mastered, and the technology for methane extraction from these deposits is more complex than traditional production of natural gas.

In [11], the cost of gas extraction from methane-hydrates in the Arctic is estimated at 200% of the cost of extracting traditional gas, and from the bottom marine gas-hydrate deposits (using the decompression method) – \$430 ... \$1600 per thousand cubic meters.

Japanese researchers estimate the cost of methane extraction from bottom gas--hydrates at \$540/thousand m^3 [12].

Given the complexity in determining the cost of gas production from methane--hydrate deposits, we use the indicator (coefficient) of economic efficiency *E*, which is convenient for comparing their economic efficiency in the first approximation, to assess the relative economic efficiency of the facilities in question.

For two-purpose plants, we define *E* in terms of the ratio of the sum of the specific values of gas and fresh water at the output from the facilities to the specific capital costs for installation:

$$E_2 = \frac{c_g(1-g) + c_v \cdot k_v}{c_p} \tag{3}$$

where:

c_g – cost of gas-methane,
c_v – cost of fresh water,
k_v – takes into account the ratio of received fresh water and methane gas,
$g = Q_t/Q_h$ – share of gas spent for combustion in a gas turbine plant for driving pumps and compressors,
$Q_t = L_m/\eta_k$ – the heat of combustion of gas-methane spent in gas-turbine plant-for driving pumps and compressors,
c_p – capital installation costs.

The expression for determining *E* single-purpose gas production units will take the form:

$$E_1 = \frac{c_g(1-g)}{c_p} \tag{4}$$

Table 2 shows the results of calculations of the economic efficiency coefficients of single-purpose and dual-purpose gas production units operating according to the three methods of methane-hydrate deposits considered above with g_g = \$1/ kg of gas, c_v = \$0.02/ kg fresh water, c_p = \$5/ (m^3 of gas-methane).

Table 2

Results of calculations of the economic efficiency coefficients of plants operating in the above three methods of developing methane-hydrate deposits

n/n	Determined values	Method of gas-hydrate reservoir development		
		1	2	3
1	The coefficient of economic efficiency of a single-purpose plant E_1, %	3	7	10
2	The coefficient of economic efficiency of the dual-purpose plant E_2, %	5	10	12

From the analysis of the results shown in Table 2, it follows that a dual-purpose plant operating on the basis of the method of injecting warm water into the well is the least cost-effective, and acting on the basis of methane replacement in hydrates of CO_2 is most effective. The coefficients of economic efficiency of the dual-purpose units are higher than those of the corresponding gas-producing single-purpose ones, but the most advantage of the combined development of the methane-hydrate deposit is manifested for the installation using the injection of warm water into the well.

4. CONCLUSIONS

The technology of development of bottom gas-hydrate deposits, which allows receiving fresh water simultaneously with methane, is considered. Principal schemes are presented and ways of operation of dual purpose facilities implementing this technology are described on the basis of the methane-hydrate gas production methods most prepared for practical implementation:

1) pumping warm water into the well,
2) depressive effect on the deposit,
3) substitution of methane in hydrates with carbon dioxide, pumped into the reservoir.

On the basis of the heat balance of a single volume of the gas-hydrate deposit, an expression was obtained for determining the amount of decrease in its temperature with a depressive effect on the deposit. It is shown that in two-purpose plants operating with the replacement of methane in hydrates with carbon dioxide, the amount of fresh water obtained is proportional to the coefficient of the recycling rate of CO_2.

Methods for calculating estimates on the basis of specific indicators of the energy and economic efficiency of methane-hydrate deposit development along with the production of fresh water are proposed. Analysis of the results of the calculations performed showed that the most effective are dual-purpose plants operating using the method of substitution of methane in hydrates with carbon dioxide. The coefficients of economic efficiency of dual-purpose installations are no less than 1.2 times higher than the similar coefficients of single-purpose gas production facilities.

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