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USE OF ALTERNATIVE ENERGY SOURCES TO IMPROVE THE EFFICIENCY OF NATURAL GAS HYDRATE TECHNOLOGY FOR GAS OFFSHORE DEPOSITS TRANSPORTATION

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ABSTRACT

Purpose. Justification of the principal schemes acceptable for the existing level of technology, methods of extraction and transportation of offshore natural gas deposits. Increase in their efficiency by maximum reduction of energy consumption resulting from complex considerations of thermal and physical properties and parameters of the system components interaction. The work is focused on the improvement of borehole products preparation system according to the gas hydrate technology during the development of offshore gas fields. The research objects were thermodynamic parameters of the system "gas – water – gas hydrate" in a vertical pipeline under nonadiabatic conditions.

Methods. Analysis and generalization of the results obtained from the complex experimental research. Mathematical modeling and software development.

Findings. The technology of gas transfer into a gas hydrate form without energy consumption for phase transition was proposed. The expediency of gas deposits development by its binding into the gas hydrate form during passage through the sea layer in the appropriate thermobaric conditions was substantiated. Mechanism of the alternative energy sources use for the production of gas hydrates, as the most energy-consuming process in technology of transporting gases in the form of gas hydrates, was grounded.

Originality. The principle possibility of binding the extracted gas into the gas hydrate form due to the energy of the productive layer and salt water was estimated. A mathematical model and software product for the description of the hydrate formation process in the presence of excess water in a vertical pipe under non-adiabatic conditions were developed.

Practical implications. The proposed gas hydrate technology creates important prerequisites for the development of small- and medium remote gas deposits, improves the efficiency and competitiveness of technology for marine transportation of natural gas in hydrate form.

Keywords: *natural gas, extraction, gas hydrates, FPU platform, phase transition, heat transfer, mathematical model*

1. INTRODUCTION

Growing global energy demands brought about the necessity to develop new oil and gas fields (Giavarini & Hester, 2011; Lu, 2016) unconventional hydrocarbon deposits (Mykhailov, 2016) as well as conventional primary energy resources (Petlovanyi, Lozynskyi, Saik, & Sai, 2018). Consequently, the technologies of transportation and storage of extracted minerals are constantly improving (Javanmardi, Nasrifar, Najibi, & Moshfeghian, 2005; Dychkovskyi et al., 2018).

In view of this, natural gas is definitely the most acceptable resource in terms of environmental impact and technological use. According to the British Petroleum report of 2015, global natural gas reserves constitute approximately 6607 billion m^3. However, nearly half of that amount is assumed to be stranded and associated gas that is not economical for market delivery because of its remoteness from potential markets and lack of transportation infrastructure. First of all it concerns offshore deposits, though their share is growing rapidly with each passing year. But the demand for natural gas from offshore fields is continuously increasing. Despite this, traditional technologies for its transportation often turn ineffective, especially in the case of remote offshore deposits with small gas reserves. Construction of pipelines to such deposits is unprofitable. Especially it concerns LNG technology.

In recent years, liquefied natural gas (LNG) has become the preferred method of natural gas transportation for large distances, particularly across the ocean. However, LNG projects will be profitable only for sufficiently large volumes of gas and a considerable transport distance (Economides, Sun, & Subero, 2006). At present, there are several alternative gas transportation technologies at the various stages of implementation: compressed natural gas (CNG), gas in natural gas hydrate form (NGH), gas-to-liquids (GTL), and gas to electricity (GTW). Each of these technologies, with all its advantages and disadvantages, can be applied for the transportation of gas from offshore deposits. Though NGH technology has been around for a long time (Gudmundsson, Parlaktuna, & Khokhar, 1994; Gudmundsson & Børrehaug 1996), it has not been fully appreciated yet, since it is still at the stage of technological processes development and improvement.

2. DEVELOPMENT THE TECHNOLOGY OF THE CONVERSION OF EXTRACTED NATURAL GAS OF MARINE DEPOSITS INTO GAS HYDRATE FORM

The technology based on the ability of gas and water molecules to form gas hydrates has been actively developing in recent years. Methane clathrates, known as methane hydrates or gas hydrates, are crystalline solid hydrocarbon compounds formed when methane gas is trapped within the crystalline water structure at low temperatures (5 – 15°C) and high pressures (2 – 3 MPa) (Sloan, 2003). One cubic meter of hydrate can store approximately 150 – 170 cubic meters of natural gas depending on thermobaric conditions and the gas composition (Makogon, 2010).

Enormous amounts of natural gas can be extracted from NGH reserves available worldwide. Approximately 98% of them are concentrated in the World Ocean at depths ranging from 200 to 700 m, and in the bottom sediments with thickness of 400 – 800 m. Hence, their development does not require drilling of the ultra-deep wells. Gas hydrate reserves in the world are reported to vary widely within the range between $10^{15} – 10^{18}$ m^3 (Birchwood et al., 2010; Maksymova, 2018). The amount of methane gas within these NGHs is estimated to be $2.1 \cdot 10^{16}$ m^3, which is more than all carbonaceous fuel reserves of the planet (Boswell & Collett, 2011).

Studies have shown that gas hydrates in the appropriate conditions remain stable for a sufficiently long time and can be used to transport gas at considerable distances (Gudmundsson, Parlaktuna, & Khokhar, 1994). Therefore, hydrates are a feasible way to transport and store natural gas in large quantities (Gudmundsson, Graff, & Kvaerner, 2003; Kanda, 2006).

The storage of natural gas in the gas hydrate form was first proposed by Benesh (1938) (produced at 283 K and the pressure of 35 MPa, stored at 241 K, i.e. in conditions close to the equilibrium) (Khokhar, 1998). The fact that natural gas hydrate contains not only gas but also water makes NGH technology the safest. In addition, the processes of formation, storage and melting of the gas hydrate take place in rather mild thermobaric conditions, in comparison with compression pressure (25 MPa) for CNG or with the temperature of 111 K for LNG. Hydrates are usually stable at moderate temperatures and pressures when compared to the conditions required for LNG and CNG (Bondarenko, Svietkina, & Sai, 2017). The scheme incorporating natural gas hydrates can be an economically preferable solution for the production, storage, and transportation of natural gas from deep water reserves to the shore.

Since Gudmundsson & Børrehaug (1996) proposed the first concept of hydrates utilization in natural gas transportation, some companies and organizations got engaged in the research into this issue. Through these investigations, it was established that NGH could be transported under atmospheric pressure at the temperature around 253 K because NGH has a self-preservation effect. A Japanese consortium, led by Mitsui Shipbuilding Co., managed to commercialize natural gas distribution via a supply chain incorporating NGH (Satoo, 2012). The comparison of capital expenditures incurred during realization of LNG and NGH projects is given in (Gudmundsson, Graff, & Kvaerner, 2003). The latter technology was 23 – 27% more efficient. In addition, the capacity of the gas hydrate production lines can be 4 times lower compared to the LNG production line, without increasing its cost. This allows for smooth adjustment of production to the change in demand for natural gas (Gudmundsson, Parlaktuna, & Khokhar, 1994). Research has identified a number of advantages inherent to the technology of gas transportation in gas hydrate form (NGH).

But the arguments in favor of this technology were not convincing enough to stimulate significant investments in its refinement and practical implementation. The research was based on the fact that processes involved in the gas hydrate production and its melting were carried out at the expense of traditional energy sources (for example, a part of the gas). Therefore, calculation of transportation costs included the cost of the energy used. At the same time, in the case of NGH-technology, these operations are the most energy consuming.

Besides, the granulated gas hydrate was considered the main form for this technology (Gudmundsson, 1996), though it has a number of disadvantages (Dawe, Thomas, & Kromah, 2003). As a rule, granular hydrates tend to freeze into a monolyth which complicates unloading. Consequently, they fill only 78% of the volume of vehicles or storages (Gudmundsson, Graff, & Kvaerner, 2003). Furthermore, much of the total granules surface area and the system of open channels between granule channels induce the process of volumetric dissociation in the gas hydrate mass. Preserving stability at the atmospheric pressure needs additional costs for cooling to temperatures below 258 K. Here, large monolithic blocks become a good solution.

For industrial implementation of gas transportation technology in gas hydrate form, it is necessary to enhance its commercial attractiveness and improve its economic efficiency. This can be achieved by sharply reducing energy costs related to the technological process. As noted above, the main part of energy in NGH-technology is consumed by phase transitions (processes of production and melting of gas hydrate) (Bondarenko & Sai, 2018). Therefore, it is impossible to

reduce these costs without violating the fundamental laws. Considering the properties of gas hydrates and specifics of gas extraction from offshore deposits, it is possible to carry out the technological processes at the expense of the environment energy (Bondarenko, Ganushevych, Sai, & Tyshchenko, 2011).

A method of producing a gas hydrate in the form of large size blocks, preserved in the ice layer, is proposed in the patent (Pedchenko & Pedchenko, 2013). Suitability of such gas hydrate blocks for long-term storage at atmospheric pressure and slightly subzero temperature (270 K) is discussed in Pedchenko & Pedchenko (2012) and Pedchenko & Pedchenko (2016).

The technology of transportation and storage of gas hydrate blocks is substantiated, its economic advantages are also defined. In addition, the authors developed a design for mobile land storages and the technology of their maintenance. To increase the efficiency of technology, it is proposed to melt gas hydrate using solar energy.

In the case of offshore gas fields development, the NGH technology efficiency can be increased by optimizing gas hydrates production. Intensive gas hydrate formation requires creation of a maximum phases interface area (gas – water) and the removal of heat produced during the exothermic process. The extracted gas exiting the well has a certain reserve of the reservoir energy. On the way to the consumer, this energy is quickly spent on gas preparation and friction in the pipeline during transportation. Additionally, in offshore deposits, the process of well products transfer above sea bottom level is accompanied by heat transfer with seawater through the walls of the pipeline. All the mixture is cooled at the average seawater temperature of 278 K. Cooling of gas during the extraction process may also occur because of its throttling (Joule-Thomson effect). As a result, thermobaric parameters in the flowline can reach the conditions of hydrates formation which will start in the presence of condensed water. Although hydrates formation is accompanied by heat release, the temperature in the pipeline does not achieve the equilibrium value due to heat transfer with seawater. Thus, the process of hydrates formation will continue, which is undesirable under the existing technology because it leads to the formation of hydrate cork and requires significant costs for its prevention (gas drying, introduction of process inhibitors, heating of the products).

However, in the case of the NGH technology implementation, it would be logical to use the existing sea body potential (high pressure, relatively low temperature, source of water) and gas (reservoir energy) for gas hydrate production. The optimal configuration takes advantage of conditions ensuring NGH formation in situ. The proposed method generates NGH in such ocean region where the combination of pressure and temperature inherently contributes to their formation, kinetics and thermodynamics. The scheme of the technological process is presented in Figure 1. It combines the method for the conversion of gas extracted from the well into the gas hydrate form using the energy of the sea and gas flow. The final product of the process is the cooled blocks, covered with an ice layer.

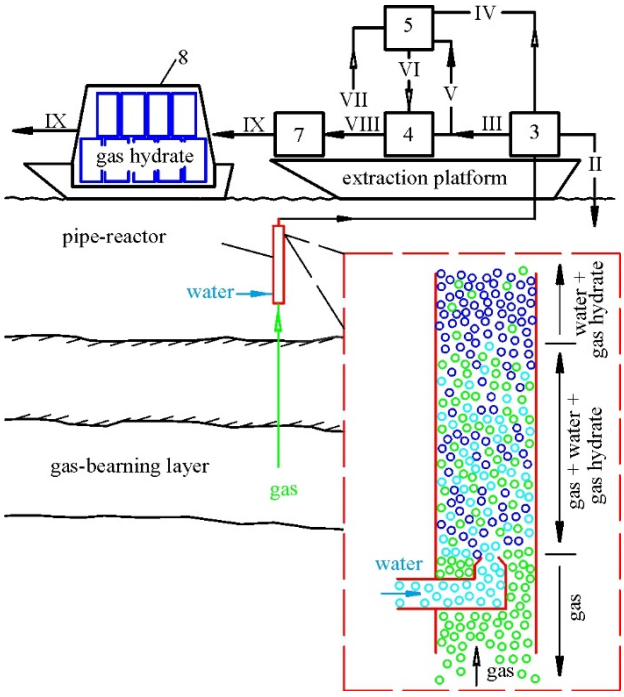

Figure 1. Schematic diagram of technology for the conversion of extracted natural gas from offshore deposits into the gas hydrate form: 1 – well; 2 – pipe-reactor; 3 – elements of the system for gas hydrate mass preparation; 4 – formation of gas hydrates blocks; 5 – gas hydrate compression; 6 – preservation of gas hydrate blocks in ice layer; 7 – transportation of gas hydrate; flows: I – gas hydrate pulp; II – water discharge; III, V – moist gas hydrate; IV, VII – low pressure gas; VI – compressed gas; VIII – gas hydrate blocks; IX – gas hydrate blocks covered with ice

Based on these considerations, the authors of (Pedchenko & Pedchenko, 2016) proposed a method of joint development and transportation of products from gas and gas hydrate offshore deposits in gas hydrated form.

In accordance with this method (Fig. 1), the gas from the production well *1* being in contact with the water flow in the pipe-reactor *2*, gives the heat to the surround-ding seawater, binds into the gas hydrate and forms a mixture of water and gas hydrate (gas hydrate pulp). Gas hydrate in the pulp (flow *I*) is fed onto FPU platform, where it is concentrated and formed into the gas hydrate blocks. Gas-hydrated blocks are transported by sea and stored in gas hydrate storages until the time of consumption.

Thus, the purpose of the work is to estimate the principle possibility of binding gas from offshore deposits (during the contact of gas and water in a vertical pipe) into the gas hydrate using alternative energy sources (energy of the productive reservoir and low potential energy of sea water), as well as to determine the main parameters of the technological process.

Since experimental research and field tests involve significant material and financial costs, the authors have developed a mathematical model of this process and the corresponding software product for its realization which are discussed further on in this paper.

3. ANALYTICAL AND EXPERIMENTAL STUDY OF GAS HYDRATE FORMATION

Let us consider the vertical pipe of diameter $d = 0.3$ m (Fig. 1), which connects the offshore gas well and the FPU platform (i.e., the pipe passes through the thickness of water). The gas extracted from the well moves through the pipe. At some distance (depth) from the platform, the gas is throttled to the pressure of 5 MPa and cooled as a result of the Joule-Thomson effect. Immediately next to the place of throttling, the jet pump injects sea water into the pipe proportionally to the gas volume 1/1.15 (1/56 in normal conditions) at the pressure of 5 MPa. Taking into account the ratio of phases volume under this pressure, the mixture of sea water and gas moves further along the pipe with a considerable area of the phase contact. However, thermobaric parameters of this section of the pipeline will meet the conditions for the gas hydrates formation. Therefore, the solid phase of the gas hydrate will appear in the flow.

Since the gas hydrate formation takes place with the release of thermal energy, the intensity of the solid phase formation (and, consequently, the ratio of the phases volumes in the flow) will depend on the intensity of the heat transfer between the mixture (water, gas and gas hydrate) in the pipe and seawater. The section of the pipeline, where all the gas will be bound into the gas hydrate, can be considered a hydrate formation reactor. This reactor uses local energy of the gas flow and a low-potential energy of seawater to sustain the process. So, the problem is to determine the minimum length of the reactor and, consequently, the optimum depth for the placement of the gas throttling node and input of sea water.

Curve *1* in Figure 2 (obtained experimentally) corresponds to the equilibrium thermobaric parameters of the hydrate formation process for fresh water and gas (CH_4 – 92.8%, C_2H_6 – 5.1%, C_3H_8 – 2.1%).

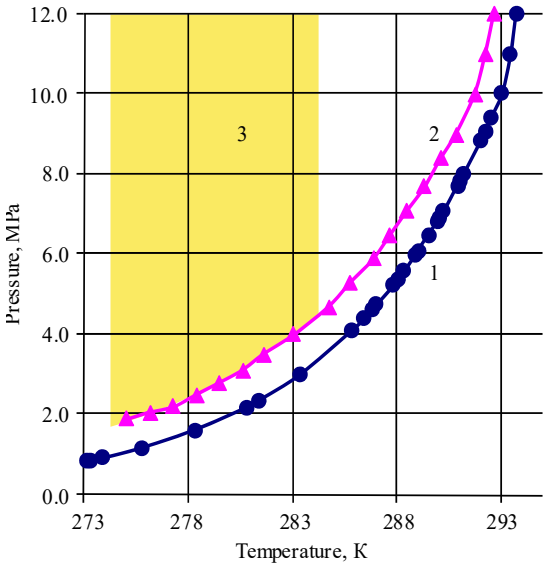

Figure 2. Equilibrium hydrate formation curves for systems "fresh water – natural gas" (curve 1) and "sea water of variable mineralization in the pipe-reactor – natural gas" (curve 2); 3 – region of hydrate formation parameters for sea water and natural gas mixture in the pipe-reactor

This curve is described by the dependence:

$$\ln P = 37.21 - \frac{9582.62}{T}. \quad (1)$$

The enthalpy of hydrate formation ΔH_1 for the gas of this composition was determined by the formula given in (Mork, 2002):

$$\ln P = \frac{-\Delta H_1}{zR \cdot T_{equil}} + const,$$

or

$$\ln P = \frac{-\Delta H_1}{zR^*} \cdot \frac{1}{T_{equil}} + const, \quad (2)$$

where:

ΔH_1 – heat released during formation of 1 mol of hydrate from water, J/mol;

z – coefficient of gas compressibility;

R^* – universal gas constant, J/(mol·K);

T_{equil} – equilibrium temperature for pressure P, K;

const – a constant.

The value of ΔH_1 for the temperature T_{equil} is determined graphically (Fig. 3) with respect to the value of the line inclination $\ln P = f(1/T)$ (dependence of the equilibrium pressure on the temperature in the system "gas – water – gas hydrate" in logarithmic coordinates):

$$\Delta H_1 = -zR^* \cdot \frac{d(\ln P)}{d\left(\frac{1}{T_{equil}}\right)} = -zR^* B, \quad (3)$$

where:

B – coefficient of the line inclination.

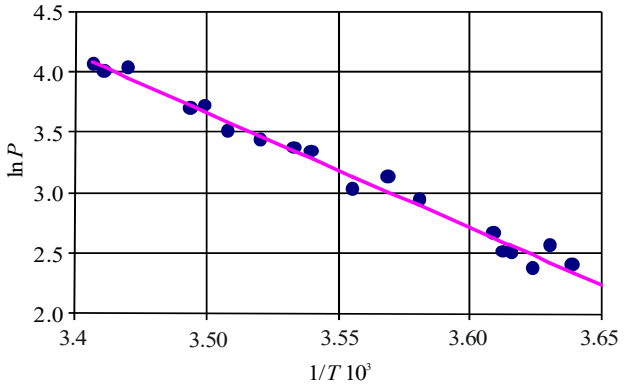

Figure 3. Dependence of equilibrium pressure on temperature in the system "gas – water – gas hydrate"

To obtain the formula for the gas hydrate of this composition, the hydration number n was calculated by the Forkran's method (for the lower quadrupole point) (Degtyarev & Bukhgalter, 1976):

$$n = \frac{\Delta H_1 - \Delta H_2}{\Delta H_3} = 6.81, \quad (4)$$

where:

ΔH_2 – heat released during formation of 1 mol of hydrate from ice, J/mol;

ΔH_3 – the energy of melting 1 mol of ice, J/mole (at T = 273.1 K, it is 6008 J/mol).

According to the results of experimental data processing for the temperature range 273.1 – 289.3 K and the pressure range 0.77 – 5.82 MPa, the studied gas hydrate mass had the following parameters: hydration number (n) – 6.81 mol H_2O/mol of gas, the heat of hydrate formation – 78.04 kJ/mol.

Sea water enters the pipe-reactor. The content of soluble salts in the water of the Black Sea, for example, is 2%. However, there are no salt ions and other admixtures in the composition of gas hydrate. As a result, their concentration in water gradually increases during the whole process of hydrate formation. According to the preliminary calculation, it has increased to 4.2%. Due to such concentration, the equilibrium curve for the system "fresh water – natural gas" has shifted to the left by 1.07 – 2.31 K (Fig. 4).

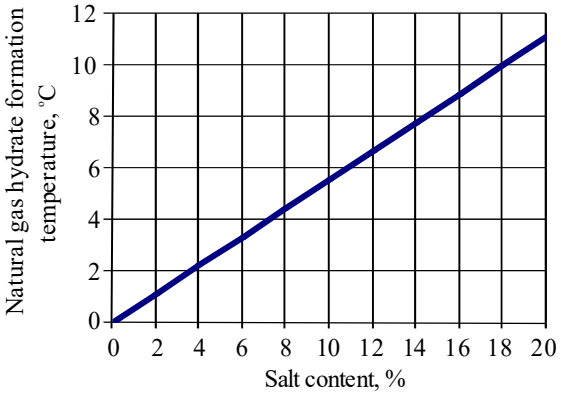

Figure 4. Relationship between the decrease of the natural gas hydrate formation temperature and the salt content in water (Smirnov, 1990)

This fact has been taken into account in the calculations. The equilibrium curve of hydrate formation for the "sea water – natural gas" system was plotted taking into account the process of salt ions concentration in the pipe-reactor (Fig. 2, curve *2*).

Based on the data obtained, we determined the thermobaric parameters of hydrate formation in the pipe-reactor: the pressure at the bottom of the pipe (P_{init}) was 5 MPa, at the top (P_{fin}) – 3 MPa, the temperature of the mixture at the bottom of the pipe (T_{init}) – 278 K, at the top (T_{fin}) – 280 K. The area delineated by these parameters is shown in Figure 2.

The temperature along the length of the pipe-reactor will change. Since gas hydrates can form throughout its length, and the volume of the gas phase will depend on the pressure in the corresponding section of the pipe, the mixture density will vary with height (depth) but it will reach the maximum after complete exhaustion of the gas phase. Concentration of gas hydrate in the water-hydrated mixture, according to (Pedchenko, 2013) was taken to be 33%. This is necessary to prevent formation of hydrate plugs in the pipeline. Hence, the maximum density of the mixture ρ_{max} was 1004.5 kg/m^3.

It was assumed that the liquid-gas mixture moved in a slug (plug) regime, when the gas bubbles plug the pipe section and intersperse with the liquid and hydrate particles. The flow velocity v was 0.35 m/s. Reynolds number in this case was 103.960. Thus, the movement of the mixture in the pipe-reactor is turbulent. The flow velocities in the near-wall area and in the center are approximately equal. Therefore, it is not reasonable to study the temperature change along the pipe diameter.

The size of the bubbles affects the velocity of their movement and homogeneity of the mixture. At the same time, the rate of gas hydrate formation depends on the interface area. That is, for intensification of the gas hydrates formation, gas bubbles should be the smallest in size.

Since the mixture flow velocity is 0.35 m/s, the maximum radius of bubbles is determined by the formula:

$$\nu = (1+1.05)\cdot(9.8_{bubbl})^{0.5}. \quad (5)$$

Then the bubbles radius will be 0.001 – 0.002 m.

Let us consider the processes in the system "seawater – natural gas – gas hydrates" which occurs during the flow motion along the pipe-reactor. The temperature of the sea water (T_{sea}) is 278 K, while the initial temperature of the mixture ($T_{mix\ init}$) is 273.3 K (taking into account the temperature of throttled gas and sea water and their mass ratio). So $T_{sea} > T_{mix\ init}$. Therefore, in the initial section of the pipe-reactor, thermal energy will flow from the outside through its wall and heat the mixture. The process will continue until the mixture temperature in the pipe reaches 278 K and will comprise:

a) heat transfer between the mixture and seawater through the wall, which is described by the equation:

$$Q_{sea} = \alpha\left(T_{sea} - \overline{T}_{inside}\right)S_{surface}\tau_1 =$$
$$= 2\alpha\left(T_{sea} - \frac{T_{278}+T_{init}}{2}\right)\pi r\varpi\tau_1^2, \quad (6)$$

where:

α – heat transfer coefficient, W/(m^2·K);

T_{278} – time, s;

ω – mixture flow velocity in the pipe, m/s;

r – radius of the pipeline, m;

b) heat radiation during the gas hydrate formation:

$$Q_{gh_1} = Hm_{278} = HV\rho_{gh} = H\pi r^2\omega\tau_1\rho_{gh}, \quad (7)$$

where:

H – enthalpy of hydrate formation, J/kg;

m_{278} – mass of the formed gas hydrate, kg.

The total temperature change over time τ_{278} in the sector of volume $S_{sect}\omega\tau$ corresponds to the sum $Q_{sea} + Q_{gh}$, and is determined by:

$$Q_{fin_1} = c\rho_1 S_{\sec t}\omega\tau_1\left(T_{init} - T_{fin}\right) =$$
$$= c\left(\rho_0 + \ldots\ln\omega\tau_1\right)\pi r^2\omega\tau_1\left(T_{init} - T_{fin}\right), \quad (8)$$

where:

c – specific thermal conductivity, J/(kg·K);

ρ_0, ρ_1 – density of the mixture at the beginning and at the end of the process, kg/m^3.

Since $Q_{sea} + Q_{gh} = Q_{fin}$, then:

$$2\alpha\left(T_{sea} - \frac{T_{278} + T_{init}}{2}\right)\pi r\varpi\tau_1^2 + H\pi r^2\omega\tau_1\rho_{gh} =$$

$$= c\left(\rho_0 + \ldots\ln\left(\omega\tau_1\right)\right)\pi r^2\omega\tau_1\left(T_{init} - T_{fin}\right). \quad (9)$$

The mixture in the pipe-reactor will quickly heat to the sea water temperature. When $T_{sea} \le T_{sum_1}$, the thermal energy of hydrate formation process will be released through the pipe wall. Then the sea water will cool the mixture that moves along the pipe. Since the diameter of the pipe-reactor (d) is much smaller than the length (L) ($d << L$), we will treat it as a rod. The peculiarities of heat transfer in such a rod are considered below.

The rod (Fig. 5) is in thermal equilibrium with sea water whose temperature (T_{sea}) is 278 K. The initial temperature of the rod is assumed to be equal to the temperature of water and is described by the function $T_r(x, 0) = f(x)$.

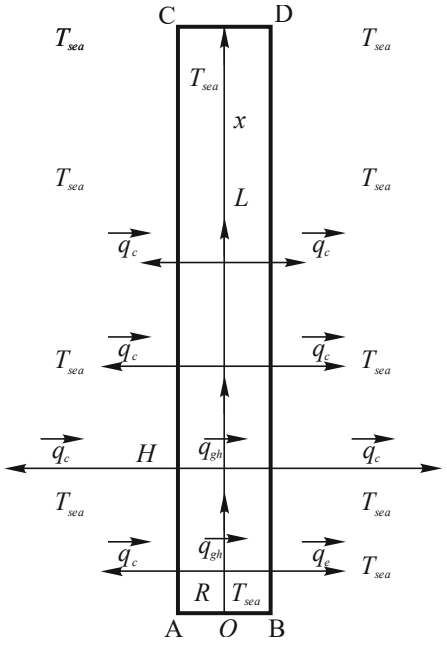

Figure 5. Physical model of temperature distribution in the rod (pipe-reactor) without heat insulation of the lateral surface

Gas hydrates can form all the time along the length of the rod. This process is accompanied by the release of energy, mixture heating and changing of the rod density according to the law:

$$\Delta\rho = a\ln\left(x - b\right), \quad (10)$$

where:

x – length of the rod (pipe-reactor), m;

b – constant.

The accumulated heat of gas hydrate formation in the rod was taken as its source. Since the lateral surface of the rod was not insulated, heat transfer with seawater was always governed by the Newton's law. The heat transfer from the lateral surface to the environment was taken into account in the differential equation as a source of thermal energy with a negative sign. It is vital that the temperature distribution along the length of the rod be detected at any time. On the basis of the obtained dependence, it is necessary to determine the length of the pipe-reactor section, where the gas will completely bind into the gas hydrate.

The length value can be established when the mixture temperature drops to 276 – 278 K. To derive an equation that describes this process, let us define the rod volume (pipe-reactor) $dxdS$. Then, thermal energy $qxdSd\tau$ will have penetrated inside through the dS_{AB} wall with the area $dS_{CD} - qx + dxdSd\tau$ during a certain period of time. The amount of energy released through the uninsulated side wall per unit of time is:

$$q_{S_{surf}}dS_{surf}d\tau = \alpha\left(T_{rod} - T_{sea}\right)2\pi rdxd\tau. \quad (11)$$

Gas hydrate is formed along the length of the rod with heat release. The mixture density in the allocated volume varies with height:

$$Hdm = Hd\rho dSdx. \quad (12)$$

The allocated rod's volume accumulates the energy:

$$\left(q_{x+dx} - q_x\right)dSd\tau - q_{S_{surf}}dS_{surf}d\tau + Hd\rho dSdx. \quad (13)$$

This will cause the temperature change in the allocated volume $c\rho(T_{fin} - T_{init})\,dSdx$. The energy change in the allocated volume per time unit is:

$$\left(q_{x+dx} - q_x\right)dS - q_{S_{surf}}dS_{surf} + \frac{Hd\rho dSdx}{d\tau} =$$

$$= c\rho\left(T_{fin} - T_{init}\right)\frac{dSdx}{d\tau}. \quad (14)$$

Then the energy change per unit of volume will be:

$$\frac{\partial q}{\partial x} - \frac{2\alpha}{r}\left(T_{rod} - T_{sea}\right) + \frac{Hd\rho}{d\tau} = \frac{c\rho\partial T}{d\tau}. \quad (15)$$

The final equation describing temperature change in the rod (pipe-reactor) looks:

$$\lambda\frac{\partial^2 T}{\partial x^2} - \frac{2\alpha}{R}\left(T_{rod} - T_{sea}\right) + \frac{Hd\rho}{d\tau} = \frac{c\rho\partial T}{d\tau}. \quad (16)$$

The function $T_{rod}(x, \tau)$ describes the temperature change in the rod and the initial conditions:

$$T_{rod}\left(x, 0\right) = T_{mix_1} \text{ for } 0 < \tau;\ 0 < x < \infty;$$

$$T_{sea} = T_{mix_1}. \quad (17)$$

Boundary conditions for the rod bottom end:

$$T_{rod}\left(0, \tau\right) = T_{mix_1} \text{ for } 0 < \tau. \quad (18)$$

The point in the pipe-reactor, where the thermal energy is not released any more (the internal source will stop working), will correspond to the point of gas hydration process completion. Therefore, after a certain period of time, the rod temperature will drop and become stable, at the value approximately equal to the temperature of sea water T_{sea}. Since the rod is semi-limited, the boundary condition for its other end will be:

$$T_{rod}(\infty,\tau) = T_{sea} \text{ for } 0 < \tau . \quad (19)$$

In some point of the rod, the temperature of flow will become stable during τ time and close to the temperature of seawater (T_{sea}). Completion of the gas hydrate formation process corresponds to the maximum temperature of the rod (and mixture in the pipe-reactor, point *H*) (Fig. 6).

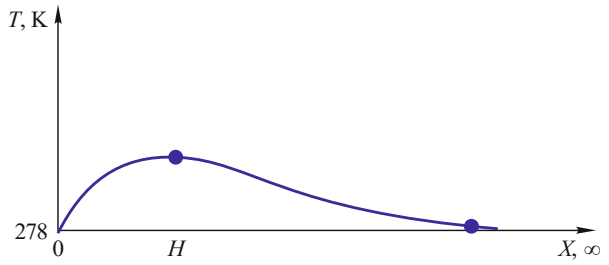

Figure 6. Scheme of heat transfer process between the pipe and seawater

In order to obtain the numerical solution of the problem, we applied the finite-difference method (mesh method). The calculation of the gas hydrate formation process was performed in Matlab environment. The resulting graph is shown in Figures 7, 8.

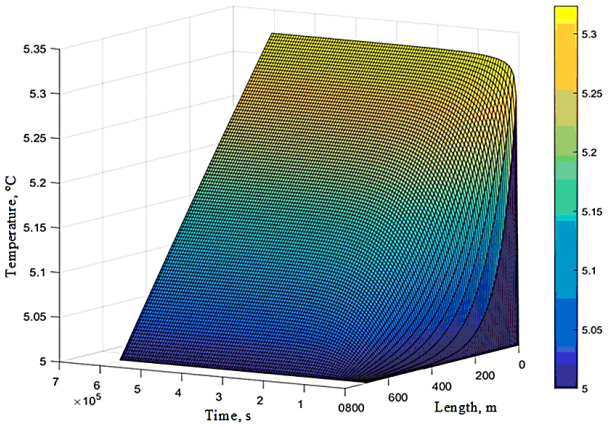

Figure 7. Heat transfer in a vertical pipe during gas hydrate formation (T, L, τ)

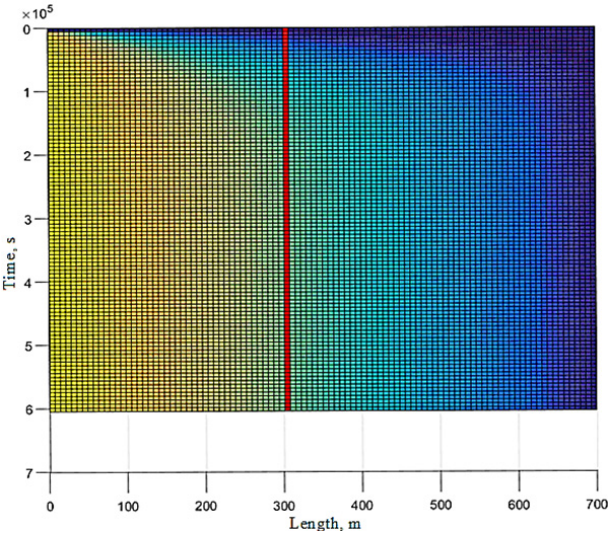

Figure 8. Heat transfer dynamics in the pipe-reactor during 168 hours (7 days)

As an example, we considered the dynamics of the heat transfer process in a vertical pipe-reactor for 7 days (168 hours). Analysis of the obtained graphs showed that the gas flow will completely become a part of gas hydrate composition in the pipe-reactor section 305 m long.

The dynamics of the heat transfer process in the pipe section 305 m long is shown in Figure 9. The temperature was observed to stabilize since the second day.

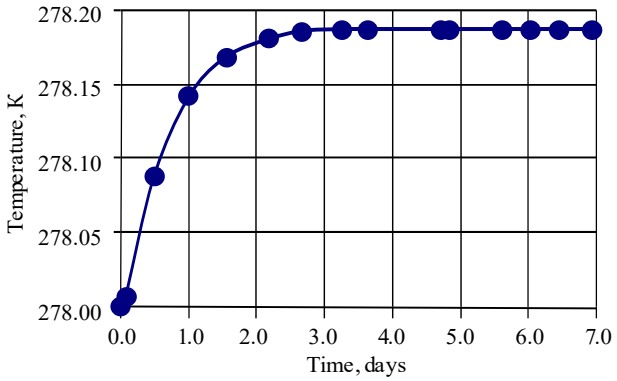

Figure 9. Graph of the mixture temperature change (stabilization) for 7 days in 305 m long pipe-reactor

4. CONCLUSIONS

The technology of gas transportation in gas hydrate form is promising because it is necessary to diversify natural gas supplies to Ukraine and develop offshore hydrocarbon deposits.

As a result of the mathematical modeling of hydration process in a vertical pipe-reactor immersed in the sea, the following conclusions were made:

1. Taking into account that $x \to \infty$, the rod (mixture) is observed to cool to the temperature of sea water $T(x, \tau) \approx T_{sea}$.

2. Testing of the model during 7 days has confirmed its adequacy.

3. The process of gas hydrate formation was completed in the point with the maximum temperature along the pipe-reactor, which is the result of the gas full binding into the gas hydrate. After that, the temperature starts decreasing.

4. Under these conditions, the length of the pipe-reactor ensuring the entire binding of the gas flow into the gas hydrate will be 305 m.

5. The density of the obtained 33% mixture of water and gas hydrate will be 1004.5 kg/m^3. The initial density of the water-gas mixture ($\rho_{mix\ init}$) in the interface was 722.6 kg/m^3.

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ВИКОРИСТАННЯ АЛЬТЕРНАТИВНИХ ДЖЕРЕЛ ЕНЕРГІЇ ДЛЯ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ГАЗОГІДРАТНОЇ ТЕХНОЛОГІЇ ТРАНСПОРТУ ГАЗУ МОРСЬКИХ РОДОВИЩ

Л. Педченко, К. Нємченко, Н. Педченко, М. Педченко

Мета. Підвищення ефективності технології транспорту газу морських родовищ шляхом максимального зниження енерговитрат на основі дослідження термодинамічних параметрів системи "газ – вода – газовий гідрат" у вертикальному трубопроводі за неадіабатних умов.

Методика. В роботі використано комплексний науково-методичний підхід, що включає аналіз літературних та інформаційних джерел, що стосуються енерговитрат при газогідратних технологіях, основні положення термодинаміки, аналітичні та експериментальні дослідження. Експериментальні дослідження проведені на ділянці вертикального трубопроводу, що моделює з'єднання морської газової свердловини із видобувною платформою, в якому рухається видобутий зі свердловини газ. Ділянка трубопровода розглядалась як реактор гідратоутворення, де досліджувались термобаричні умови формування гідрату. Для встановлення формули газогідрату використано метод Форкрана. Для чисельного розв'язання процесу утворення газових гідратів застосовано метод кінцевих різниць, а розрахунок процесу гідратоутворення виконано у середовищі Matlab.

Результати. Запропоновано технологію переведення газу у газогідратну форму без витрати енергії на фазовий перехід. Доведено доцільність розробки газових родовищ шляхом зв'язування газу в газогідрат за рахунок наявності необхідних термобаричних умов при його проходженні крізь морську товщу. Обґрунтовано передумови і механізм використання альтернативних джерел низькопотенційної енергії для виробництва газогідрату як найбільш енерговитратного процесу технології транспортування газів у газогідратній формі.

Наукова новизна. Надана наукова оцінка принципової можливості зв'язування видобутого газу у газогідратну форму за рахунок енергії продуктивного пласта і низькопотенційної енергії морської води. Розроблено нову математичну модель та алгоритм у програмному продукті для опису процесу гідратоутворення при надлишку води за неадіабатних умов у вертикальній трубі, що омивається водою.

Практична значимість. Запропонована газогідратна технологія створює важливі передумови розробки малих та середніх віддалених родовищ газу, підвищення ефективності й конкурентоздатності технології морського транспортування природного газу у газогідратній формі.

Ключові слова: *природний газ, видобування, газові гідрати, видобувна платформа, фазовий перехід, теплообмін, математична модель*

ИСПОЛЬЗОВАНИЕ АЛЬТЕРНАТИВНЫХ ИСТОЧНИКОВ ЭНЕРГИИ ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ ГАЗОГИДРАТНОЙ ТЕХНОЛОГИИ ТРАНСПОРТА ГАЗА МОРСКИХ МЕСТОРОЖДЕНИЙ

Л. Педченко, К. Немченко, Н. Педченко, М. Педченко

Цель. Повышение эффективности технологии транспорта газа морских месторождений путем максимального снижения энергозатрат на основе исследования термодинамических параметров системы "газ – вода – газовый гидрат" в вертикальном трубопроводе при неадиабатных условиях.

Методика. В работе использован комплексный научно-методический подход, включающий анализ литературных и информационных источников, касающихся энергозатрат при газогидратных технологиях, основные положения термодинамики, аналитические и экспериментальные исследования. Экспериментальные исследования проведены на участке вертикального трубопровода, моделирующего соединение морской газовой скважины с добывающей платформой, в котором движется добытый из скважины газ. Участок трубопровода рассматривался как реактор гидратообразования, где исследовались термобарические условия процесса формирования гидрата. Для получения формулы газогидратов использован метод Форкрана. Для численного решения процесса образования газовых гидратов применен метод конечных элементов, а расчет процесса гидратообразования выполнен в среде Matlab.

Результаты. Предложена технология перевода газа в газогидратную форму без затрат энергии на фазовый переход. Доказана целесообразность разработки газовых месторождений путем связывания газа в газогидрат за счет наличия необходимых термобарических условий при его прохождении через морскую толщу. Обоснованно предпосылки и механизм использования альтернативных источников низкопотенциальной энергии для производства газогидратов как наиболее энергозатратного процесса технологии транспортировки газов в газогидратной форме.

Научная новизна. Дана научная оценка принципиальной возможности связывания добытого газа в газогидратную форму за счет энергии продуктивного пласта и низкопотенциальной энергии морской воды. Разработана новая математическая модель и алгоритм в программном продукте для описания процесса гидратообразования при избытке воды в неадиабатных условиях в вертикальной трубе, омываемой водой.

Практическая значимость. Предложенная газогидратная технология создает важные предпосылки разработки малых и средне удаленных месторождений газа, повышение эффективности и конкурентоспособности технологии морской транспортировки природного газа в газогидратной форме.

Ключевые слова: *природный газ, добыча, газовые гидраты, добывающая платформа, фазовый переход, теплообмен, математическая модель*

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