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INCREASING THE THERMAL RESISTANCE OF SHELL GAS-SUPPORT STRUCTURES FOR USE AS GAS HYDRATES STORAGE

Currently, in the world and Ukraine there are difficulties with the provision of natural gas. However, one of the problems is its storage. So, the object of research is the process of storing natural gas in land storages in gas hydrate form. An alternative to traditional technologies can be the transportation and long-term storage of natural gas in the form of gas hydrates. However, the existing reinforced concrete and metal structures, in addition to a significant price, also cannot sufficiently provide effective thermal insulation of the gas hydrate and its tightness.

The paper substantiates the possibility of using gas support structures and pneumatic building structures as gas hydrate storage facilities. The possibility of improving the proposed structures by using non-hardening foams as a thermal insulation material has been proposed and confirmed by calculations. The study was aimed at calculating and analyzing the effectiveness of such a method of thermal insulation of a ground gas storage facility for storing natural gas in gas hydrate form.

A method acceptable for the current level of technology development is proposed for increasing the thermal resistance of gas support structures for their use as gas storages in the gas hydrate state. It consists in using stable liquid foams as an effective thermal insulation material to fill the space between the layers of a two-layer coating. In the course of the study, the high efficiency of the proposed method of thermal insulation of ground hydrate reservoirs with stable liquid foams was shown.

Calculation of thermodynamic characteristics of gas support storages for gas hydrates at their thermal insulation by liquid foam is made. The efficiency of the technological process of storing gas hydrate in the form of blocks is analyzed depending on the time of year. The main parameters of operation of such facilities are substantiated. It has been established that storage of hydrate blocks in storage without their dissociation during insulation with a layer of foam requires short-term additional cooling during the summer period of storage. Thus, this technology has prospects for widespread adoption.

Keywords: ground shell gas support structures, gas hydrates, stable foam, thermal resistance, gas storages.

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1. Introduction

The reliability of the fuel and energy complex and the energy security of the state depend on the uninterrupted operation of the technological chain of production, transportation and storage of hydrocarbons.

Its uninterrupted operation can be ensured when, for 1 ton of annual increase in hydrocarbon production, the increase in storage capacity will be 0.3–0.4 m³. Therefore, the organization of a sufficient capacity of the hydrocarbon storage system is the main condition for the effective functioning of the industry.

For many countries of the world, natural gas is the basis of energy. It is stored in various states of aggregation in underground and ground storage facilities. As a rule, underground gas storage (UGS) facilities are linked to

main gas pipelines, gas fields, gas liquefaction plants. In cases where small deposits are exploited, there are no gas transportation mains, and the construction of gas liquefaction plants is unprofitable, storage of natural gas in gas hydrate form can become an alternative to existing technologies. At the same time, it is proposed to use shell gas support structures as gas hydrate storage facilities [1, 2].

Therefore, it is important to study the possibility of using such ground-based shell gas-supported storage facilities and conduct a study of their effectiveness.

2. The object of research and its technological audit

The object of research is the process of storing natural gas in aboveground storage facilities in gas hydrate form.

Storage of gas hydrates for a long period requires maintaining appropriate pressure and temperature conditions to prevent regasification. Often, the storage pressure and temperature parameters do not lie in the region of hydrate formation. The stability of the gas hydrate mass under non-equilibrium conditions can be increased by its forced or spontaneous coating with an ice shell [3].

The papers [3, 4] substantiate the technology of production of blocks from the gas hydrate mass, preserved with a layer of ice. They can be stored and transported under non-equilibrium thermobaric conditions (temperatures around minus 3 °C and atmospheric pressure). However, the condition for their long-term storage is effective thermal insulation. At the same time, the gas hydrate blocks themselves can act as cold accumulators. Therefore, taking into account the level of development of building technologies, shell gas support structures (closed structures «lying» on a gas cushion, the pressure in which exceeds atmospheric pressure only to compensate for the weight of the shell [1]) are proposed as storage facilities for long-term storage of gas hydrate blocks. The use of this type of surface hydrate storage can significantly even out seasonal fluctuations in gas consumption and become an alternative to underground storage.

The main element of gas support structures is a soft shell. However, the thermal performance of such shells is low. They cannot provide sufficient thermal resistance. To increase it during the construction of gas hydrate storage facilities, a two- and three-layer coating of gas support structures is proposed. Excess pressure in pneumatic two- and three-layer structures is distributed between the layers of the shell. This allows increasing the bearing capacity and shaping stability of the structure without increasing the strength of the structural material. A two-layer reinforced polymer coating up to 2 mm thick will provide high-quality sealing at a relatively low pressure (0.2–0.3 MPa) [5] (Fig. 1).

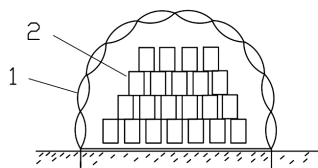


Fig. 1. Scheme of the hydration reservoir:
1 – elastic two-layer shell; 2 – gas hydrate blocks

In gas support structures for the storage of gas hydrate (formed into blocks), it is necessary to maintain a temperature regime that allows the gas hydrate to be in a stable state at low pressure.

During the year, the temperature regime of such storage to prevent the dissociation of gas hydrate is proposed to be provided due to the cold of the gas hydrate mass and additional cooling, which should compensate for the heat from solar radiation during the warm season.

The thermal resistance of the coating, which characterizes the heat-shielding characteristics of such a gas storage facility, is determined by the formula:

$$R_{coat} = \frac{1}{\alpha_{ex.air}} + \frac{2\delta_{PVC}}{\lambda_{PVC}} + R_{bar} + \frac{1}{\alpha_{in.air}}, \quad (1)$$

where R_{coat} – the reduced thermal resistance of the hydrate reservoir coating, $m^2 \cdot K/W$; $\alpha_{ex.air}$ and $\alpha_{in.air}$ – the heat transfer

coefficients of external and internal air, respectively, $W/m^2 \cdot K$; δ_{PVC} – PVC layer thickness, m; λ_{PVC} – coefficient of thermal conductivity of the PVC layer, $W/m \cdot K$; R_{bar} – thermal resistance of the barrier layer, $m^2 \cdot K/W$.

For calculation, let's took the average temperature of January and July for the forest-steppe zone: January – 265 K, July – 293 K [6, 7].

The thermal resistance of the hydration reservoir coating (R_{coat}) for winter and summer will be 0.34 and 0.28 $m^2 \cdot K/W$, respectively. Then in winter heat will come to the storage:

$$q_{wint} = \frac{1}{R_{coat}}(t_{out} - t_{in}) = \frac{1}{0.34}(-8 - (-15)) = 20.58 \text{ W/m}^2, \quad (2)$$

where t_{out} and t_{in} – the air temperatures, respectively, from the outside and in the storage, K.

The heat flux in the hydration reservoir in summer (q_{sum}) will be [8, 9]:

$$q_{sum} = q_o + \beta \cdot A_q = 1/R_{coat} \cdot ((t_{out} + \rho_{abs} \cdot J_{av} / \alpha_{out}) - t_{in}) + \beta(0.5 \cdot A_{tm} + \rho_{abs}(J_{max} - J_{av}) / \alpha_{out}), \quad (3)$$

$$q_{sum} = 104.19 \text{ W/m}^2,$$

where q_o – the average daily heat input to the storage, W/m^2 ; A_q – the daily amplitude of heat flux fluctuations, W/m^2 ; β – the coefficient that determines the change in the value of the heat flux A_q depending on the hour of the day; t_{out} – the outdoor air temperature in July, K; t_{in} – the air temperature inside the storage, K; ρ_{abs} – the coefficient of solar radiation heat absorption by the outer surface of the storage; J_{av} – the average daily amount of heat of the total solar radiation falling on the storage surface in the warmest month, MJ/m^2 ; α_{out} – the coefficient of heat absorption of the outer surface of the storage facility for the warm period of the year; A_{tm} – the maximum amplitude of daily fluctuations in air temperature in the warm month of the year, °C; J_{max} , J_{av} – maximum and average daily value of the sum of solar radiation, MJ/m^2 .

The results of calculations of the thermodynamic parameters of gas hydrate storage in ground gas storage facilities are given in Table 1.

Table 1
Parameters of storage of natural gas hydrates
in ground gas storage facilities

Thermodynamic parameters	Calculations for the average monthly temperature	
	winter	summer
Thermal supports, $m^2 K/W$:		
– heat transfer, R_{av}	0.23	0.09
– PVC coating, R_{PVC}	0.025	0.025
– air barrier layer, R_{bar}	0.22	0.18
– coating, R_{coat}	0.34	0.28
Heat flux of gas hydrate without heat-insulating layer, q , W/m^2	20.58	104.19

According to the performed calculations (Table 1), one of the most problematic places is a significant heat flow entering the gas hydrate storage without a heat-insulating layer. Then, taking into account the thermal resistance of

the two-layer coating of the hydrate reservoir, its thermal inertia will be:

$$D_{coat} = 0.27 \cdot R \sqrt{\lambda \rho c} = 0.27 \cdot 0.28 \cdot \sqrt{0.0244 \cdot 1.29 \cdot 717} = 0.4, \quad (4)$$

where D – thermal inertia; R – thermal resistance, $m^2 \cdot K/W$.

The calculation of the thermal inertia of the two-layer coating of the hydrate reservoir showed its inertialessness ($D_{coat} < 1.5$). At the same time, the gas hydrate layer has a large inertia ($D_{gh} > 7$). Consequently, the air layer between the storage coating and the gas hydrate mass (blocks) heats up much faster than the gas hydrate itself. Therefore, even through a two-layer coating, a significant heat flux will enter the hydrate storage.

To reduce the heat flux through the two-layer coating in storage and minimize the cost of cooling, it is necessary to increase the thermal inertia and thermal resistance of the coating.

3. The aim and objectives of research

The aim of research is to propose high-quality thermal insulation of a ground-based shell gas storage facility for storing natural gas in gas hydrate form.

To achieve the aim set, the following objectives must be completed:

1. Analyze options for increasing the thermal resistance of ground gas support structures.
2. Determine and compare the thermodynamic parameters of ground gas storage facilities with different thermal insulation for storing natural gas in the gas hydrate state.

4. Research of existing solutions to the problem

Therefore, gas hydrates of natural gas, prepared according to the method described in [4], are capable of being in a stable state for a long time at atmospheric pressure and a slight negative temperature. Sufficient conditions for such storage are high-quality thermal insulation and tightness of storage facilities.

Options for organizing natural gas storages in the gas hydrate state are presented in [10, 11].

As a repository, a deepened permanent structure is proposed, the walls of which are lined with thermal insulation material. The cavity involves a roof made of a transparent material for the ingress of sunlight and regulation of the intensity of hydrate melting during gas extraction.

However, the use of a capital structure made of traditional building materials (reinforced concrete, metal structures and bricks) as a storage facility cannot provide the necessary thermal insulation and sufficient tightness. Therefore, structures of this type do not meet the requirements of modern energy projects.

In addition, classical building structures have a longer installation time and higher operating costs for pneumatic structures [12].

Ground-based gas-supported pneumatic structures can be used as storage facilities as an alternative option [12]. Types of ground gas support structures that can be used as ground storage facilities are analyzed in [12, 13].

However, the authors of all these works do not consider the influence of the thermal resistance of shell structures on the process of their operation.

The shell material of a pneumatic structure has a significant impact on the performance of the structure. The works [13, 14] analyze the types of shells that can be used.

High-quality sealing at a pressure slightly exceeding atmospheric pressure (for example, 0.2–0.3 MPa) will be provided by a polymer film of minimal thickness [15]. Taking into account the insignificant specific mass of the sealing film coating, the mass of the enclosing elements of the storage will be insignificant [16].

Modern polyester-based coatings will provide high performance characteristics of these buildings for 15–20 years [12]. Based on polymer films and high-strength synthetic fabrics, multilayer composite materials have been created. At the same time, their strength is increased by reinforcement with fabrics [6]. Fluorine-containing polymers are also successfully used to prolong the life of shells [14]. However, in all works the question of the most effective material for storage shells remains open. The best solution is coverage, in which each of the components is selected according to a certain set of conditions.

Air-supported structures require only a small amount of pressure to support them and withstand the wind load. In [17], it was proposed to fill the cavities between the multilayer coatings of gas support structures with gases (helium, coal gas, hydrogen). However, this solution will not solve the problem of their low thermal resistance.

Thermal resistance can be increased by placing an additional film with a mirror coating under the shell to reflect thermal radiation [12]. As a result, the thermal conductivity coefficient can be reduced to $1.7 \text{ W}/(m^2 \cdot K)$ [14].

At the same time, an effective thermal insulation of an object can be provided by a relatively insignificant layer of porous insulation (foam plastic, mineral wool, etc.) [15].

Sufficiently high thermal resistance is provided by materials with closed spherical bubbles 0.1–2.0 mm in diameter. Their air is practically motionless and has the lowest thermal conductivity of all materials, $0.023 \text{ W}/m \cdot K$ [18].

The main characteristics of foams are their multiplicity and stability over time. Since the multiplicity of liquid foams has a value of $\beta \leq 20$, then, according to the classification, their structure is made up of spherical bubbles separated by thick layers of liquid. The stability of foams stabilized with macromolecular compounds increases with their concentration. Therefore, a relatively high-quality thermal insulation of a structure can be provided by a non-hardening layer of polymer foams [19].

Thus, it is advisable to use gas support pneumatic structures as an alternative to capital structures for storing natural gas in gas hydrate form. At the same time, in order to significantly increase their thermal resistance, it is advisable to use solid polymeric stable foams with a high level of stability (thermal conductivity coefficient not higher than $0.04 \text{ W}/(m^2 \cdot K)$) as a thermal insulation material between coating layers.

5. Methods of research

Calculation and analytical methods were used to study the efficiency of using the proposed ground gas support structures as gas storage in gas hydrate form.

6. Research results

A schematic diagram of a hydrate storage organized according to the proposed method is shown in Fig. 2.

The storage is a gas-supported ground structure, thermally insulated with a layer of liquid foam. Its main elements are shelter, base and auxiliary equipment.

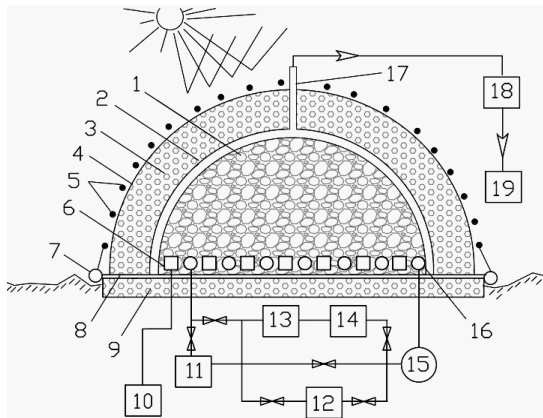


Fig. 2. Schematic diagram of land-based mobile hydrate storage:

1 – gas hydrate; 2 – the lower web of an elastic and impervious to gas and water material; 3 – layer of liquid foam; 4 – the upper sheet of elastic and impervious to water and gas material, covered with a sun-reflecting layer; 5 – mesh of ropes; 6 – system of perforated pipes for sampling gas and water from under the gas hydrate stack; 7 – hermetic connection of the sheets of the shelter and the base; 8 – coating of the base from a material impervious to gas and water; 9 – solid heat-insulating material; 10 – water tank; 11 – solar collector; 12 – coolant heater; 13 – refrigeration unit; 14 – air cooler; 15 – pump; 16 – heat exchanger in the form of a pipe system; 17 – gas sampling line; 18 – compressor; 19 – gas consumption

Let's consider the features of storing natural gas hydrate in the form of blocks manufactured in accordance with the proposed technology, using the example of a gas-supported ground storage facility with a capacity of 2870 tons of gas hydrate for storing 5.2 million m³ (under normal conditions) of natural gas.

The diameter of a hemispherical dome for such an amount of hydrate will be 50 m. As a coating, a reinforced two-layer coating of polyvinyl chloride (PVC) 2 mm thick was taken, which has the following characteristics:

- coefficient of thermal conductivity:

$$\lambda_{PVC}=0.16 \text{ W/m}\cdot\text{K};$$

- thermal resistance:

$$R_{PVC}=0.002/0.16=0.0125 \text{ m}^2\cdot\text{K/W} [14].$$

To fill the space between the coating layers, a stable foam with a density of 4.0 kg/m³ and a thermal conductivity coefficient $\lambda_{PVC}=0.041 \text{ W/(m}\cdot\text{K)}$ was taken. For calculation – a layer of foam with an average thickness of 1–1.5 m.

The total heat balance of the hydrate reservoir is described by the equation:

$$Q_{out}-Q_{add}+Q_{soil}-Q_{col.HM}=0, \quad (5)$$

where Q_{out} – the heat entering the storage from the outside, J; Q_{add} – additional cooling, J; Q_{soil} – the heat flow from the earth's surface, J; $Q_{col.HM}$ – cold accumulated in the hydrated mass (blocks), J.

To prevent gas hydrate dissociation, additional storage cooling should compensate for the amount of heat coming from outside above its stability level.

To determine the value of heat flows entering the storage through the coating from the outside (Q_{out}), it is necessary to establish the heat-shielding characteristics of the storage. The reduced thermal resistance of the coating (R_{coat}) is determined by the formula:

$$R_{coat}=\frac{1}{\alpha_{out.air}}+\frac{2\delta_{PVC}}{\lambda_{PVC}}+\frac{\delta_{SF}}{\lambda_{SF}}, \quad (6)$$

where R_{coat} – the reduced thermal resistance of the hydrate reservoir coating, m²·K/W; α_{air} – the heat transfer coefficient of the outside air, W/(m²·K); δ_{PVC} – PVC film layer thickness, m; λ_{PVC} – coefficient of thermal conductivity of the PVC film layer, W/m·K; δ_{SF} – the thickness of the stable foam layer, m; λ_{SF} – the thermal conductivity of the stable foam layer, W/m·K.

Based on the calculations performed, the reduced thermal resistance of the hydration reservoir coating (R_{coat}) for winter and summer will be 25.28–37.78 and 25.12–37.62 m²·K/W, respectively.

Then in winter the hydration storage will receive heat from outside:

$$q_{win}=\frac{1}{R_{coat}}(t_{out}-t_{in})=\\=\frac{1}{37.78}(-8-(-25))=0.45 \text{ W/m}^2, \quad (7)$$

where t_{out} and t_{HM} – the air temperatures outside and in the storage, respectively, °C.

Taking into account the surface area of the storage, the total heat flux to the storage through the coating in the winter period will be $Q_{in.win}=1.76 \text{ kW}$.

The heat input to the storage in summer (q_{sum}) was determined by the formula:

$$q_{sum}=1/R_{bar.sum}(((t_n+\rho_{abs}\cdot J_{av}/\alpha_n)-t_{in})+\\+\beta\cdot(0.5\cdot A_{tm}+\rho_{abs}(J_{max}-J_{av})/\alpha_n)), \quad (8)\\q_{um}=1.33 \text{ W/m}^2.$$

The heat flow through the storage surface will be $Q_{out.sum}=5.23 \text{ kW}$.

The heat flux entering the gas hydrate mass from the soil (Q_{soil}), with its average annual value for the middle latitudes of 0.17 W/m² [8, 9], through the area of the base of the storage will be 0.3 kW. Its insulation will reduce the heat input to 0.25 kW.

Therefore, a comparison of the obtained calculated thermodynamic parameters of gas hydrate storage in ground-based gas-supported storage facilities with different thermal insulation is given in Table 2.

Fig. 3 shows the dependence of the amount of heat entering the storage on the gas hydrate storage temperature and the outside air temperature.

So, according to Fig. 3 storage of gas hydrate blocks at a temperature of 258 K in winter requires heat removal of 0.9 kW, in summer at a maximum temperature of 4.44 kW.

Let's set the temperature on the surface of the gas hydrate mass as a result of the heat flow as a process of heat transfer through the multilayer coating. On one side of the coating, there is an external medium with a temperature t_{sur} , and on the other side, a cooled gas hydrate with a temperature in the center $t_{centerGH}$.

Comparison of thermodynamic parameters
of gas hydrate storage in ground gas storages

Table 2

Thermodynamic parameters	Calculations for the average monthly temperature	
	winter	summer
Thermal resistance, $m^2 \cdot K/W$: – coating without thermal insulation, R_{coat} ; – coating with a layer of stable foam, R_{SF}	0.255 37.78	0.115 37.62
Heat flow, W/m^2 : – to gas hydrate without thermal insulation, q ; – to gas hydrate with a layer of stable foam, q_{SF}	20.58 0.45	104.19 1.33
Heat flow to gas hydrate in storage, kW: – without thermal insulation, Q_{out} ; – with a layer of resistant foam, Q_{outSF}	80.77 1.76	408.95 5.23
Energy consumption for cooling, Q_{col} , kW: – without thermal insulation, Q_{col} ; – with a layer of resistant foam, Q_{col}	81.0 2.1	409.2 5.5

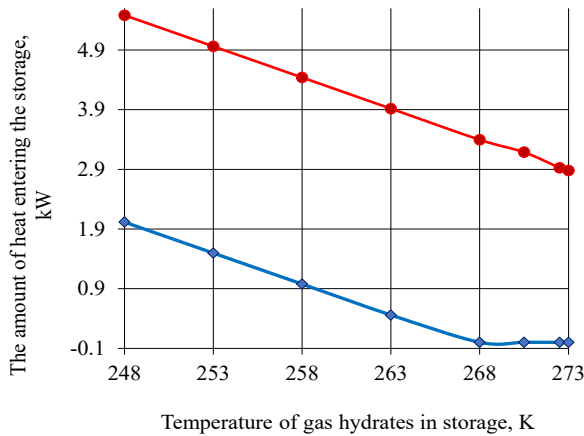


Fig. 3. Dependence of the amount of heat entering the storage on the storage temperature of gas hydrates and the outside air temperature:
— winter; — summer

Sometime before the start of dissociation of the surface of the gas hydrate mass, the temperature in the center of the storage can be considered approximately stable. The heat flow coming from the outside through the PVC coating, the stable foam layer and the gas hydrate layer to its center (Fig. 4) will be considered stationary and, according to Newton's law (convective heat transfer) and Fourier's law (conductive heat transfer), is described by the equations:

$$q = \alpha_{conv}(t_{sur} - t_{PVC1}), \quad (9)$$

$$q = \frac{\lambda_{PVC}}{\delta_{PVC}}(t_{PVC1} - t_{SF1}), \quad (10)$$

$$q = \frac{\lambda_{SF}}{\delta_{SF}}(t_{SF1} - t_{SF2}), \quad (11)$$

$$q = \frac{\lambda_{PVC}}{\delta_{PVC}}(t_{SF2} - t_{PVC4}), \quad (12)$$

$$q = \frac{\lambda_{GH}}{\delta_{GH}}(t_{PVC4} - t_{center.gh}), \quad (13)$$

where t_{PVC1} and t_{PVC4} – the temperatures on the outer surfaces of the first (outer) and second (inner) layers of the storage

coating, respectively, K; t_{SF1} – the temperature on the surfaces of the resistant foam layer, K; α_{conv} – coefficients of heat transfer by convection through the PVC coating layer and resistant foam, $W/m^2 \cdot ^\circ C$; $t_{center.gh}$ – the temperature at the center of the gas hydrate mass, K; t_{sur} – air temperature, K; δ_{PVC} , δ_{SF} and δ_{GH} – thickness of PVC layers, stable foam and gas hydrate mass (blocks); λ_{PVC} , λ_{SF} , λ_{GH} – thermal conductivity coefficients of PVC film, resistant foam and gas hydrate mass (blocks), respectively, $W/m \cdot K$.

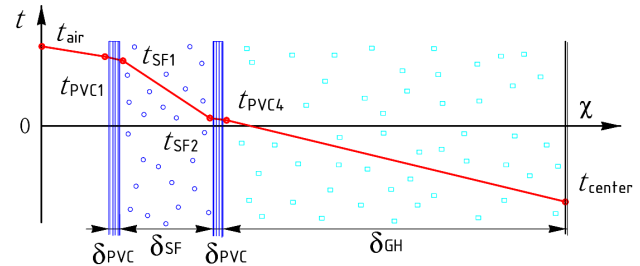


Fig. 4. The process of heat transfer in a hydrate reservoir of the gas-supported shell type: δ_{PVC} , δ_{SF} and δ_{GH} – the thickness of the layers of PVC, stable foam and gas hydrate, m; t_{PVC1} and t_{PVC4} – the temperature on the outer surfaces of the outer and inner layers of the storage coatings, $^\circ C$; t_{SF1} and t_{SF2} – the temperature on the surface of the resistant foam layer, $^\circ C$; $t_{center.gh}$ – the temperature at the center of the gas hydrate mass, $^\circ C$; t_{air} – air temperature, $^\circ C$

From the system of equations (9)–(13) let's determine the temperature of the outer surface of the inner PVC film t_{PVC4} and, at the same time, the surface temperature of the gas hydrate mass (blocks) of the storage:

$$t_{PVC4} = t_{air.gh} = \frac{(t_{air} - t_{center.gh}) \left(\frac{1}{\alpha_{out}} + \frac{2\delta_{PVC}}{\lambda_{PVC}} + \frac{\delta_{SF}}{\lambda_{SF}} \right)}{\left(\frac{1}{\alpha_{out}} + \frac{2\delta_{PVC}}{\lambda_{PVC}} + \frac{\delta_{SF}}{\lambda_{SF}} + \frac{\delta_{GH}}{\lambda_{GH}} \right)}. \quad (14)$$

Let the initial storage temperature of gas hydrates in such storage $t_{center.gh} = 248$ K. Then for the summer period ($t_{air} = 293$ K), when a stationary heat flow is set, the temperature of the gas hydrate surface, according to (14), will be $t_{PVC4} = t_{air.gh} = 272.3$ K. This indicates that additional cooling is required to maintain the gas hydrate temperature at 258 K. For the winter period, for the temperature $t_{air} = 265$ K and the gas hydrate storage temperature $t_{center.gh} = 248$ K when installing a stationary heat flow, the temperature of the outer surface of the inner PVC film t_{PVC4} and, at the same time, the surface temperature of the gas hydrate will be $t_{PVC4} = t_{center.gh} = 257.5$ K. With the stability of the gas hydrate mass at the level of 258 K, additional cooling of the gas hydrate mass will be unnecessary.

Using the calculated values obtained above; let's determine the time to reach the critical temperature on the surface of natural gas hydrates depending on the time of year and the temperature of storage with thermal insulation with stable foam.

The calculation of heat input through the two-layer coating of the hydrate reservoir showed that the foam and gas hydrate have a large inertia (D_{SF} , $D_{GH} > 7$). The heat entering the storage, starting from the surface, will gradually heat the foam and gas hydrate layer, but very slowly.

Since the thickness of the gas hydrate layer is significant, it can be considered a cold accumulator. The

temperature in its center for a long time and the setting of the non-stationary thermal regime in the surface layer can be conditionally considered unchanged. Let's determine the time during which the inner surface of the foam layer and, accordingly, the surface of the gas hydrate mass can heat up to the critical storage temperature of 258 K. To do this, use the dependencies:

$$\frac{\Theta_{PVC4}}{\Theta'} = \frac{t_{air,gh} - t_{PVC4}}{t_{air,gh} - t_{PVC4}} = f_1(Bi, Fo), \quad (15)$$

$$\frac{\Theta_{center,gh}}{\Theta'} = \frac{t_{center,gh} - t_{PVC4}}{t_{in,gh} - t_{PVC4}} = f_2(Bi, Fo), \quad (16)$$

where $t_{center,gh}$ – the initial temperature of the gas hydrate mass, K; $t_{in,gh}$ – the surface temperature of the gas hydrate mass, K; t_{PVC4} – the temperature of the PVC film layer, K; Bi, Fo – Biot and Fourier criteria.

From here let's determine the surface temperature of the gas hydrate $t_{air,gh}$ for different air temperatures (Fig. 5).

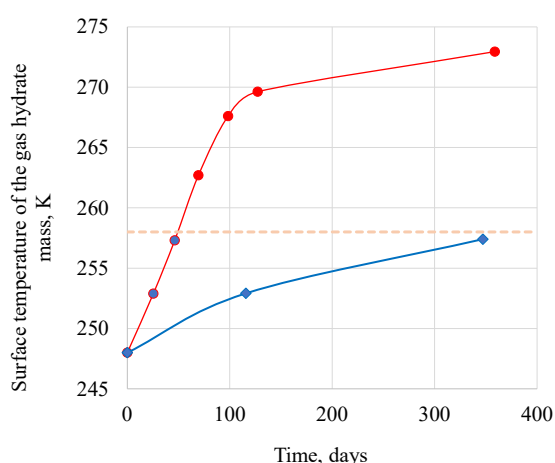


Fig. 5. Dynamics of changes in the temperature of the surface of the gas hydrate mass in the ground gas-supported storage with thermal insulation by a layer of stable foam for different air temperatures:

— outdoor temperature 293 K, the gas hydrate mass does not require additional cooling; — outside air temperature 293 K, gas hydrate mass requires additional cooling; — outside air temperature 265 K, gas hydrate mass does not require additional cooling; — stability limit of gas hydrate mass in storage

According to Fig. 5, in the case of heating the outer surface of the foam layer in summer to $t_{SF1}=293$ K, the temperature of the surface layer of the gas hydrate will be $t_{air,gh}=258$ K. Moreover, the heating process, due to the foam layer, will continue for almost 45 days. That is, for a long time in summer, gas hydrate can be stored in storage without additional cooling and its surface will not dissociate.

Only in the case of storage of gas hydrates in summer in a surface gas-supported storage with thermal insulation with stable foam for a period longer than 45 days, additional cooling is required.

In winter, at an ambient temperature of 265 K, the surface temperature of the gas hydrate mass will warm up for about 360 days. Therefore, due to the high thermal insulation properties of stable foam, it is possible to effectively store the gas hydrate mass in the proposed storage facilities without heat removal.

Therefore, storage of hydrate blocks in storage without their dissociation during conservation with a foam layer

requires only short-term additional cooling. However, when storing the gas hydrate mass (blocks) for a short period, additional cooling for these conditions is not required at all.

7. SWOT analysis of research results

Strengths. The paper proves the high efficiency of the proposed method of thermal insulation of ground-based shell gas-supported storage facilities for storing gas hydrate with a layer of liquid foam (Table 2).

Filling the space between the layers of the shell with stable foam with low density and thermal conductivity will significantly reduce thermal resistance and reduce the cost of operating ground-based gas-supported hydrate storages.

Weaknesses. It is necessary to continue studying the process of gas hydrate regasification directly in such storage facilities.

Opportunities. On the basis of the study, the effectiveness of using ground-based gas-supported shell structures as an alternative to existing technologies for storing natural gas in cases of operating small fields, lacking transport routes and unprofitable gas liquefaction plants was proved.

Threats. Research does not need additional costs when implementing the results. However, the risks of introducing technologies in the gas industry are obvious. They are connected with the inconsistency of the legislative and economic policy of the state in the field of energy saving.

8. Conclusions

1. A method acceptable for the current level of technology development is proposed for thermal insulation of a shell gas support structure when they are used as storage facilities for natural gas in the gas hydrate state. It consists in the use of stable liquid foams as an effective thermal insulation material to fill the space between two-layer coatings.

2. The calculation and comparison of the thermal resistances of the shell coating without thermal insulation and with a layer of stable foam showed significant differences, namely 0.12–0.26 and 37.6–37.8 m²·K/W, respectively.

In the case of thermal insulation of the shell gas support structure with stable liquid foams, the storage facility in summer (at a temperature of 293 K) will require additional cooling only in case of long-term storage of gas hydrates (more than 45 days). In winter (at a temperature of 265 K), the gas hydrate storage will not require heat removal at all.

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