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**STUDY OF THE PARAMETERS OF HEAT EXCHANGE OF THE STEAM PHASE OF PROPANE-BUTANE MIXTURE WITH SOIL IN AN UNDERGROUND GAS HOLDER DURING NATURAL REGASIFICATION OF LIQUEFIED HYDROCARBON GAS IN AUTONOMOUS GAS SUPPLY SYSTEMS**

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**Statement of the problem.** Gas supply of individual residential buildings with consumption of gas fuel of up to 3 kg / h in most cases is organized on the basis of individual gas holders with underground installation in the ground and natural regasification of the liquefied hydrocarbon gas. A significant disadvantage of systems with natural regasification is that when reducing wet steam mixture of propane-butane in pressure regulators, ice and hydrate plugs are formed, which disrupts the gas supply of an object. In order to develop recommendations for the prevention of specified phenomenon, the authors carried out theoretical studies of the heat exchange of the vapor phase of the propane-butane mixture above the mirror of evaporation in the underground gasholder of liquefied hydrocarbon gas.

**Results.** The mode of flow of the vapor phase of the propane-butane mixture from the mirror of evaporation to the neck of the underground gas holder is established, which makes it possible to correct the values of convective heat transfer and heat transfer coefficients recommended by other authors for an objective evaluation of processes heat exchange in the underground gasholder of liquefied hydrocarbon gas.

**Conclusions.** The results of the conducted studies showed that the process of reduction of the vapor phase can be carried out without the formation of hydrates and ice plugs in pressure regulators on the condition of the conservation of the temperature of the vapor phase of the mixture of propane-butane from the neck of the gasholder to the node of reducing.

**Keywords:** underground gas holder, liquefied hydrocarbon gas, autonomous gas supply system, convective heat transfer coefficient, heat transfer coefficient, vapor phase of the propane-butane mixture.

**Introduction.** Autonomous liquefied gas supply systems are currently a promising field in the development of energy supply of household objects. The main advantage of these systems is

that they can be set up in any climate zone regardless of the relief, properties of the soil and modes of the consumption of gas fuel [13, 15, 20, 21]. In terms of construction, systems of autonomous gas supply can be designed in two ways: systems with an artificial regasification of liquefied hydrocarbon gas.

It should be noted that systems with an artificial regasification liquefied hydrocarbon gas should be used for energy consumption of over 50 MWatth/year [2, 3]. These systems are more expensive due to an evaporation setup as part of a gas supply scheme and its features in the area where gas is being supplied (individual premises for an evaporation setup, fire-proof parts of buildings and structures, extra pipeline binding for safe regasification using liquefied hydrocarbon gas).

For inconsiderable energy consumption of objects (individual residential houses, cottages) of up to 50 MWatth/year, systems with natural regasification of liquefied hydrocarbon gas [5, 19, 26]. In this case the vapor phase of liquefied hydrocarbon gas is generated due to a heat flow of a soil mass.

According to the GOST R 52087-2003 “Liquefied Hydrocarbon Fule Gases” technical propane-butane with the component composition of over 60 % of butane.

Systems of autonomous gas supply with natural regasification become most vulnerable during the cold season when the temperature of the outside air and soil respectively on the axis of laying a gas holder is considerably lower than that of regasification of the butane fraction (about minus 0,5 °C) [14, 23, 27, 28]. In this case during reduction of the vapor phase containing a gaseous mix of propane and butane there might be icy and hydrate cloggings in the pressure controller, which causes unstable gas supply for users [4, 10, 27].

The studies of hydrate formation in liquefied hydrocarbon gas supply systems conducted in [6, 7, 9, 11, 16] indicate that formation of hydrates is possible during throttling of a saturated liquid and saturated vapors of a propane-butane mix.

A propane-butane mix comes into the pressure controller for throttling with the temperature that is formed due to heat exchange between a gas holder with liquefied hydrocarbon gas and a surrounding soil massive. Heat exchange of an isothermal cavity with soil is investigated in [18, 19, 24] where heat transfer from a soil massive to the liquid phase in a gas holder with liquefied hydrocarbon gas is elaborated. Simultaneously heat transfer from the soil massive to the vapor phase over the evaporation mirror has not been sufficiently studied, which compromises the accuracy of the studies of natural regasification and further reduction of a vapor mix.

Therefore in order to develop practical recommendations for improving reliability of liquefied hydrocarbon gas supply for hydrateless reduction of liquefied hydrocarbon gas, it is necessary to conduct extra research into heat transfer during natural regasification of liquefied hydrocarbon gas in underground gasholders with liquefied hydrocarbon gas.

**1. Theoretical study of heat transfer.** The amount of heat supplied from the soil to the vapor phase of a propane-butane mix is

$$Q = F_{n\phi}^{n.\phi} \cdot k \cdot (t_{zp} - t_{\text{жс}}), \quad (1)$$

where  $F_{n\phi}^{n.\phi}$  is the area of the surface washed by the vapor phase in the gas holder,  $\text{m}^2$ ;  $k$  is the heat transfer coefficient,  $\text{Watt}/\text{m}^2\text{K}$ ;  $t_{zp}$  is the temperature of the soil massive,  $^{\circ}\text{C}$ ;  $t_{\text{жс}}$  is the temperature of the liquefied gas in the gas holder,  $^{\circ}\text{C}$ .

In its turn the heat emission coefficient is determined as

$$k = \frac{1}{\frac{1}{\alpha_{zp}} + \frac{\delta_{zu}}{\lambda_{zu}} + \frac{\delta_p^{cm}}{\lambda_p^{cm}} + \frac{1}{\alpha_{n.\phi}}}, \quad (2)$$

where  $\alpha_{zp}$  is the heat emission coefficient of the surface soil of the hydroisolation of the gasholder,  $\text{Watt}/\text{m}^2\text{K}$  [12, 19];  $\delta_{zu}$  is the thickness of hydroisolation of the gasholder,  $\text{m}$ ;  $\lambda_{zu}$  is the coefficient of heat conductivity of hydroisolation,  $\text{Watt}/\text{mK}$ ;  $\delta_p^{cm}$  is the thickness of the wall of the gasholder,  $\text{m}$  [22];  $\lambda_p^{cm}$  is the coefficient of heat conductivity of the wall of the gas holder,  $\text{Watt}/\text{mK}$  [22];  $\alpha_{n.\phi}$  is the coefficient of heat emission from the internal surface of the wall of the gas holder of the vapor phase,  $\text{Watt}/\text{m}^2\text{K}$ .

Heat emission from the internal surface of the wall of the vapor phase due to convective and radiant heat exchange is

$$\alpha_{n.\phi} = \alpha_{n.\phi}^k + \alpha_{n.\phi}^r, \quad (3)$$

where  $\alpha_{n.\phi}^k$  is the coefficient of heat emission during convective heat exchange,  $\text{Watt}/\text{m}^2\text{K}$ ;  $\alpha_{n.\phi}^r$  is the heat transfer coefficient during radiant heat exchange,  $\text{Watt}/\text{m}^2\text{K}$ .

Radiant heat transfer of multi-atomic gases has not been fairly investigated. It has been addressed for some gases such as nitrogen, oxygen, water vapors and hydrocarbon gas, sulphurous anhydrite [8, 25, 22]. Simultaneously there are no recommendations concerning the vapor phase of hydrocarbon gases in the literature. Therefore we might assume with a reduction in the heat transfer coefficient that

$$\alpha_{n.\phi} \cong \alpha_{n.\phi}^k. \quad (4)$$

In order to get a full insight into heat transfer of a propane-butane mix to the vapor phase, it is necessary to carry out a study of the similarity criteria of Reynolds  $Re$ , Grashof  $Gr$ , Prandtl  $Pr$  and Nusselt  $Nu$ . The above similarity criteria allow for the flow modes of the propane-butane mix over the evaporation mirror and the effect of the physical properties of propane-butane on heat exchange in the gasholder.

A variable component composition of the vapor phase of the propane-butane mix during the operation of the liquefied hydrocarbon gas holder causes variable values of the similarity criteria that should be determined based on the respective proportions of the components.

Considering the above, the values of the criteria are determined using the expressions of

— Prandtl  $Pr$ :

$$Pr = \frac{v_{cm} c_p^{cm} \cdot \left[ A \cdot (\rho_{T_0}^{np} + a_{np} \cdot 10^{-4} \cdot (T - T_0)) + B \cdot (\rho_{T_0}^{\delta} + a_{\delta} \cdot 10^{-4} \cdot (T - T_0)) \right]}{A \cdot \lambda_{T_0}^{np} \cdot \left( \frac{T}{T_0} \right)^n + B \cdot \lambda_{T_0}^{\delta} \cdot \left( \frac{T}{T_0} \right)^m}; \quad (5)$$

— Grashof  $Gr$ :

$$Gr = \frac{g \beta \Delta t (0.5 d_z (1 - \phi_{\text{жс}}) + l_z)^3}{v_{cm}^2}; \quad (6)$$

— Reynolds  $Re$ :

$$Re = \frac{G d_{\text{эКВ}}}{3600 (A \cdot (\rho_{T_0}^{np} + a_{np} \cdot 10^{-4} \cdot (T - T_0)) + B \cdot (\rho_{T_0}^{\delta} + a_{\delta} \cdot 10^{-4} \cdot (T - T_0))) \cdot f_n v_{cm}}, \quad (7)$$

where  $v_{cm}$  is kinematic viscosity of the vapor phase of the propane-butane mix,  $\text{m}^2/\text{sec}$ ;  $c_p^{cm}$  is heat conductivity of the mix of the propane-butane vapors at a constant pressure,  $\text{kJ}/\text{kg} \text{ } ^\circ\text{C}$ ;  $A$ ,  $B$  is content of propane and butane in the vapor phase of liquefied hydrocarbon gas, mole %;  $\rho_{T_0}^{np}$ ,  $\rho_{T_0}^{\delta}$  is density of the vapor phase of propane and butane respectively at  $0 \text{ } ^\circ\text{C}$ ,  $\text{kg}/\text{m}^3$ ;  $a_{np}$ ,  $a_{\delta}$  are empirical coefficients depending on changes in the molecular weight of the components [17];  $T$ ,  $T_0$  are absolute temperatures of the investigated propane-butane mix and at  $0 \text{ } ^\circ\text{C}$ ,  $\text{K}$ ;  $\lambda_{T_0}^{np}$ ,  $\lambda_{T_0}^{\delta}$  is heat conductivity of the propane and butane vapors under normal conditions,  $\text{Watt}/\text{m} \text{ } ^\circ\text{C}$ ;  $n$ ,  $m$  are empirical indices of the degree [14];  $g$  is the acceleration of gravity,  $\text{m}/\text{sec}^2$ ;  $\beta$  is the coefficient of the volumetric expansion of the propane and butane vapors,  $\text{K}^{-1}$ ;  $\Delta t$  is temperature pressure between the heat exchange surface and the temperature of the vapor phase of the propane-butane mix,  $^\circ\text{C}$ ;  $d_z$  is the diameter of the gasholder,  $\text{m}$ ;  $\phi_{\text{жс}}$  is the filling level of the gasholder with the liquid phase of the liquefied hydrocarbon gas, proportions;  $l_z$  is the length of the gas holder,  $\text{m}$ ;  $d_{\text{эКВ}}$  is an

equivalent diameter of the space filled with the vapor phase of the liquefied hydrocarbon gas in the gas holder, m;  $G$  is the gas consumption, kg/h;  $f_n$  is the area of a transverse section of the vapor pillow, m<sup>2</sup>.

The study of the similarity criteria based on the expressions (5)—(7) allowed the flow mode of the vapor phase of the mix of the propane and butane vapors from the evaporation mirror to the gasholder mouth to be determined during natural regasification of the liquefied gas and individual gas consumption in residential buildings from 1.5 to 3 kg/h as a laminar viscosity-gravitation mode characterized by a combination of the criteria of Reynolds  $Re \leq 2300$  and Raley  $Ra = Gr \cdot Pr > 8 \cdot 10^5$ .

In its turn the criterion of Nusselt  $Nu$  for the viscosity-gravitation mode is given by the expression [8]

$$Nu = 0.15 \cdot (Re \cdot Pr)^{0.33} \cdot (Gr \cdot Pr)^{0.1} \varepsilon_1 \varepsilon_t, \quad (8)$$

where  $\varepsilon_1$  is a correction factor that considers the effect of hydrodynamic stabilization of the flow at the initial stage of heat exchange on heat emission [8];  $\varepsilon_t$  is a correction factor that considers the dependence of physical properties of a fluid environment on the temperature [1]. Considering that the criterion of Nusselt and the coefficient of convective heat exchange are connected with the dependence

$$Nu = \frac{\alpha_{n.\phi.}^{\kappa} \cdot d_{\text{экв}}}{\lambda_{cm}}, \quad (9)$$

where  $\lambda_{cm}$  is heat conductivity of the mix of the vapor phase of propane-butane, Watt/mK, the expression for determining the coefficient of convective heat exchange  $\alpha_{n.\phi.}^{\kappa}$  is as follows

$$\alpha_{n.\phi.}^{\kappa} = 0.15 \frac{\lambda_{cm}}{d_{\text{экв}}} \cdot (Re \cdot Pr)^{0.33} \cdot (Gr \cdot Pr)^{0.1} \varepsilon_1 \varepsilon_t. \quad (10)$$

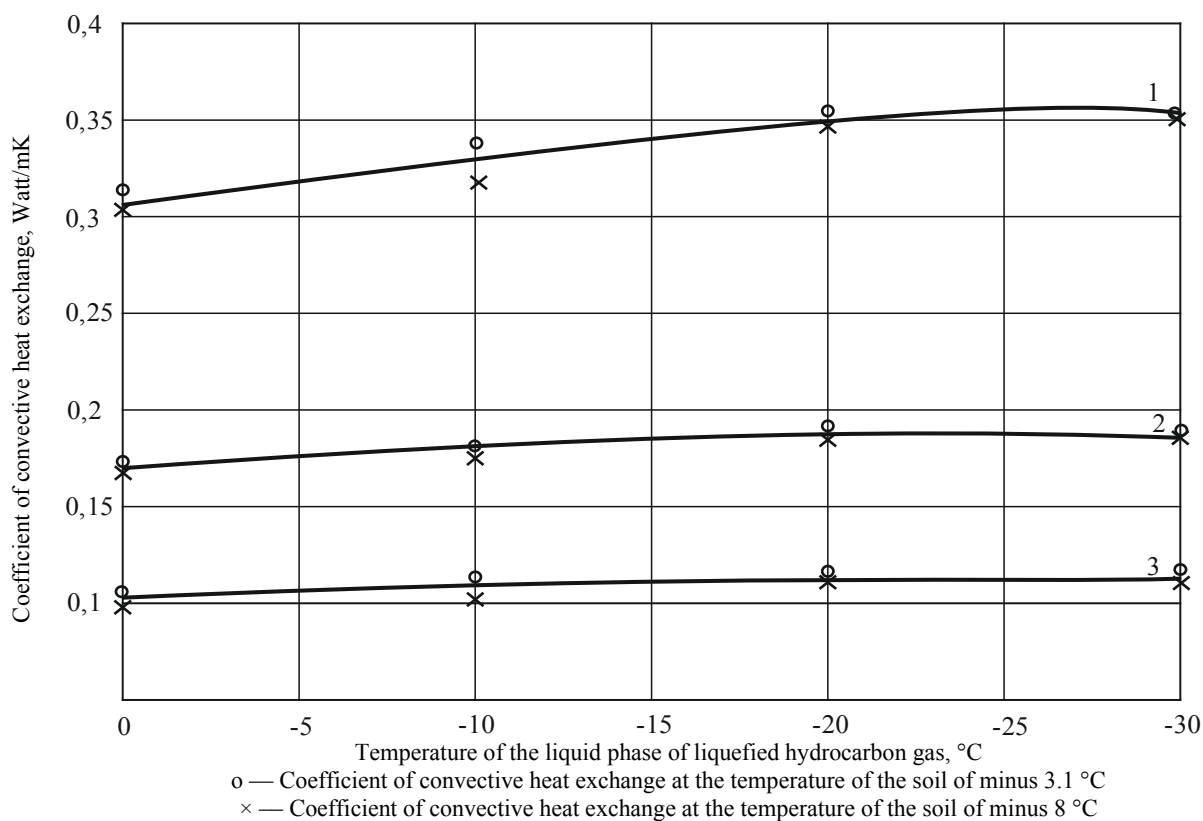
**2. Numerical solution for determining a coefficient of convective heat exchange, heat emission and overheating of the vapor phase of the propane-butane mix.** According to the expressions (1)—(10), calculations were conducted to determine the coefficient of convective heat exchange, coefficient of heat emission between the soil and vapor phase in the underground gasholder and overheating of the vapor phase for different individual modes of the operation of the vessel.

The following original data were presented for the calculation:

— The component composition of liquefied hydrocarbon gas throughout the operation of the gas holder:

- 50 % propane and 50 % butane,
  - 25 % propane и 75 % butane,
  - 10 % propane и 90 % butane;
- a filling level of the gasholder with gas during operation: 85 %; 50 %; 15 %;
- a range of changes in the temperature of the liquefied hydrocarbon gas: from 0 °C to minus 30 °C;
- the temperature of the soil in the axis of laying the underground gasholder that is typical of climate zones is according to the GOST 16350-80:
- a moderately cold climate zone is minus 3.1 °C,
  - a cold climate zone is minus 8 °C.

The results of the corresponding calculations are presented in the graphs (Fig. 1—3).



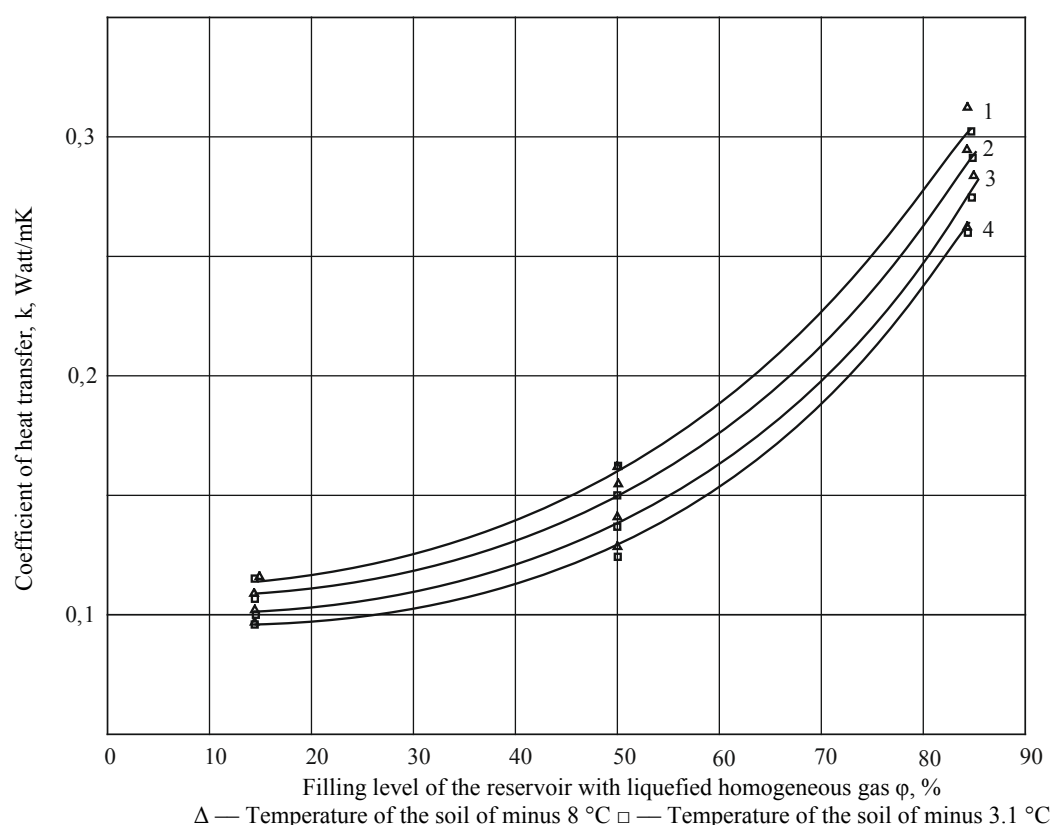
**Fig. 1.** Coefficient of convective heat exchange during operation of an underground gas holder of liquefied hydrocarbon gas: 1 is a filling level of the gasholder with the liquefied gas of 85 %; 2 is a filling level of the gasholder with the liquefied gas of 50 %; 3 is a filling level of the gasholder with the liquefied gas of 15 %

As seen from the graph (Fig. 1), the coefficient of convective heat exchange depends on the filling level of the gasholder with the liquefied gas and changes in a fairly wide range from 0.11 (the filling level of the reservoir of 15 %) to 0.36 Watt/(m<sup>2</sup>K) (the filling level of the liquefied hydrocar-

bon gas reservoir of 85 %). Considering the flow mode of the vapor phase of the propane-butane mix allows the coefficients of convective heat exchange specified in [12, 18, 19] and assumed to range from 0.05 to 0.2 Watt/(m<sup>2</sup>K) to be corrected, which provides an increase in the accuracy of the results of studies of heat exchange in underground liquefied hydrocarbon gasholders.

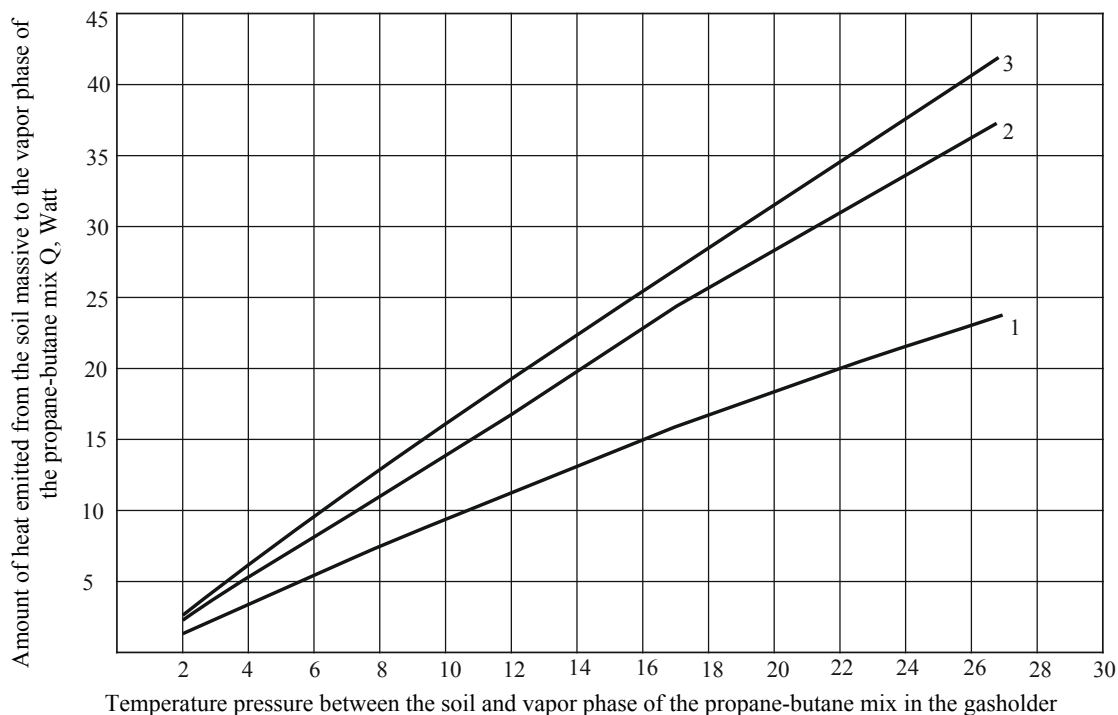
Based on the results presented in Fig. 1, the coefficients of heat transfer were obtained. The analysis of Fig. 2 showed that coefficients of heat transfer depend on the filling level of the reservoir by liquefied hydrocarbon gas and varies from 0.096 (the filling level of the reservoir with liquefied gas of 15 %) to 0.301 Watt/m<sup>2</sup>K (the filling level of the reservoir of 85 %).

An increase in the temperature pressure within the range of one level also causes a heat transfer coefficient to grow. Then, e.g., at the filling level of the gasholder with liquefied hydrocarbon gas and the temperature pressure of 2 °C the heat transfer coefficient is 0.125 Watt/m<sup>2</sup>K, at the temperature pressure of 26.9 °C the coefficient is 0.161 Watt/m<sup>2</sup>K. Therefore in order to determine a heat flow from the soil massive, it is necessary to assume that a heat transfer coefficient is differential depending on the filling level with liquefied hydrocarbon gas and temperature pressure.



**Fig. 2.** Coefficients of heat transfer from the soil massive to the vapor phase of the propane-butane mix:  
 1 at the temperature of liquefied hydrocarbon gas of minus 30 °C; 2 at the temperature of liquefied hydrocarbon gas of minus 20 °C; 3 at the temperature of liquefied hydrocarbon gas of minus 10 °C;  
 4 at the temperature of liquefied hydrocarbon gas of minus 0 °C

Using the results of the studies presented in Fig. 1 and 2 according to the equation (1), a heat flow for overheating the vapors of the propane-butane mix was determined as they move away from the evaporation mirror to the gasholder mouth (Fig. 3).



**Fig. 3.** For determining the amount of heat from the soil massive to the vapor phase of the propane-butane in the underground gasholder of liquefied hydrocarbon gas:

- 1 is the filling level of the gasholder with the liquid phase 85 %;
- 2 is the filling level of the gasholder with the liquid phase 50 %;
- 3 is the filling level of the gasholder with the liquid phase 15 %

The heat transfer of the vapor phase of the propane-butane mix causes it to heat up as it moves away from the mouth depending on the temperature pressure and filling level of the reservoir. Extra heating values are given in Table.

Table

Extra heating values of the vapor phase of the propane-butane mix over the evaporation mirror

Filling level of the gasholder with liquefied gas, %	Temperature pressure between the soil and liquid phase of liquefied hydrocarbon gas, °C					
	2	6.9	12	16.9	22	26.9
85	0.54	2.5	3.62	6.11	6.63	14.7
50	0.96	3.73	6.46	9.39	11.85	16.38
15	1.11	4.32	7.36	10.71	12.76	18.9



As seen from Table, a heat flow from the soil to the vapor phase of liquefied hydrocarbon gas provides extra heating. This causes an increase in the dryness of the vapor phase of the mix that is set to reduce. Hence e.g., in a moderately cold climate zone during regasification of liquefied hydrocarbon gas with the temperature of the liquid phase of minus 10 °C and if the reservoir is 50 % full, there are saturated vapors near the evaporation mirror (dryness of 1.0), the propane-butane mix with a maximum moisture content of 0.116 mole % [14]. While approaching the mouth of the reservoir, the vapor phase of the propane-butane mix that takes part in the heat transfer heats up by an extra of 3.73 °C. The maximum moisture content of the mix is 0.141 mole % [14] and causes an increase in the dryness of up to 0.82.

Hence the heat transfer of the vapor phase of liquefied hydrocarbon gas with the soil in the underground reservoir causes an increase in the vapor phase, which provides throttling with no moisture and hydrates.

**Conclusions.** As a result of the studies,

— it was found that during autonomous gas supply of objects with individual consumption of gas fuel of up to 3 kg/h in the gas holder from the evaporation mirror to the mouth there is laminar viscosity-gravity flow mode of the vapor phase of the propane-butane mix determining the parameters of heat transfer in the upper part of the underground gasholder;

— the coefficients of convective heat exchange and heat transfer were obtained depending on the filling level of the gasholder with liquefied gas, the composition of the liquefied gas, the temperature of the liquefied gas in the gasholder and the soil surrounding the gasholder that allow the amount of heat emitted from the soil massive of the vapor phase of the propane-butane mix to be determined more accurately;

— the amount of heat emitted from the soil massive to the vapor phase of the propane-butane mix and heating of the vapor phase over the evaporation mirror in the underground gasholder were found. The heat transfer over the evaporation mirror causes an increase in the temperature of the vapor phase that leads the maximum moisture content and the dryness of the vapor phase of the propane-butane mix to rise as well as enhances throttling with no hydrates and icy clogs in the pressure controllers provided that the vapors keep being overheated up to the reduction node.

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