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SUBSTANTIATION OF APPLICATION OF UNDERGROUND REDUCTION CHAMBER IN LIQUEFIED PETROLEUM GAS SUPPLY SYSTEMS

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Statement of the problem. When reducing the vapor phase of propane-butane in the pressure regulators of the above-ground closet gas control points, water falls out in free form and at subzero temperatures of ice and crystalline hydrates formation. In order to prevent this, methods are employed in the form of applying thermal insulation and heating the inner space of the cabinet, which significantly increases the cost of the structure and the reduction process. As an alternative, the authors set forth an underground reduction chamber. The article provides a scientific rationale for the use of this underground chamber in the practice of gas supply to consumers.

Results. The configuration of the reduction chamber has been substantiated, mathematical modeling of the heat exchange processes of the chamber with the surrounding soil massif has been performed, the thickness of the thermal insulation of the ascending section of the vapor phase and the reduction chamber has been selected, and the process of reduction of the vapor phase in pressure regulators has been simulated.

Conclusions. According to the results of the studies, the cylindrical shape is optimal for the reduction chamber, which provides the minimum total surface of the enclosing structures. The implementation of the economic and mathematical model made it possible to recommend the optimal thicknesses of the thermal insulation of the chamber and the ascending section of the vapor phase, enabling the process of throttling of the liquefied petroleum gas vapor phase in pressure regulators without the release of free water and the formation of ice and hydrate plugs.

Keywords: underground reduction chamber, liquefied petroleum gas, chamber configuration, optimal thermal insulation thickness, economic and mathematical model, simulation of the reduction.

Introduction. For supplying gas objects, regardless of their ambient temperature, the level of filling the tank with liquefied petroleum gas (LPG), the content of propane and butane in the

vapor phase, before supplying the consumer, it is essential to ensure the required pressure of the gas phase [10, 13, 18].

In order to reduce the pressure and maintaining it at a variable gas flow rate, pressure regulators are employed that are installed directly on the head of the tank or in chamber gas control points (CGCP) [20]. The most common ones are overground freestanding CGCPs [21]. However, outdoor installation and operation of the CGCPs ensures the temperature of the reduced gas equal to the ambient temperature, which, in the case of liquefied petroleum gas vapors, particularly in the wintertime, causes condensate precipitation from the propane-butane vapor phase and the formation of ice and hydrate plugs in the pressure regulators [2, 3, 17].

In order to address this drawback, gas, electric and water heating of CGCP is employed [6, 7, 11]. This causes a considerable increase in operating costs associated with the presence of external sources of supply of energy resources and additional equipment for heating [19]. Besides, an increase in the reduction temperature is achieved by means of applying thermal insulation to the elements of gas supply systems: reservoir heads, pressure regulators, piping [7, 11]. A considerable setback of the above methods is the need to apply insulation to complex relief elements of gas supply systems, which results in a limited choice of types of insulating surfacings, the complication of its application and rising construction and installation costs. As an alternative version of the CGCP, a reduction chamber is set forth buried deep into the ground [16], which implements the advantages causing a decrease in the cost of gas reduction and the entire gas supply system from the reservoirs as a whole. These benefits are as follows:

- 1) the possibility of using the heat of the soil mass to maintain higher temperatures compared to the ambient air temperature for the sake of reduction;
- 2) the absence of additional energy sources used to heat the camera body;
- 3) a decrease in the length of the vapor phase pipeline, which ensures the movement of vapors to the reduction chamber along the linear part located in the soil, with a higher temperature and in an unsaturated state.

Considering the considerable cost of the gas tank supply systems for consumers, the development of a technical solution that allows one to ensure uninterrupted supply of consumers in the process of reducing capital investments and operating costs is a highly relevant task.

Therefore the objective of the study is to substantiate the configuration and operation modes of the underground reduction chamber, which provides hydrate-free reduction of vapors of liquefied hydrocarbon gas before they are supplied to the user.

1. Substantiation of the optimal configuration of the underground reduction chamber.

Concrete is suggested as a material for the manufacture of the chamber, which is common in water supply systems, sewerage systems and heating networks in the form of a square and rectangular configuration or cylindrical wells. The advantages of such structures are as follows:

- industrialization of manufacturing;
- a wide range of products;
- absence of corrosive processes of the product body.

The coefficient of thermal conductivity of concrete is almost 25 times less than that of the thermal conductivity of steel, which contributes to the high resistance of the chamber walls to the heat transfer. While selecting the optimal configuration of the reduction chamber, the condition of minimizing the surface was observed to ensure minimum heat losses to the environment as well as the possibility of servicing the pressure regulator in the chamber, provided that the latter had the minimum overall dimensions. This condition is met by a minimum size of 0.7 m, which allows for the maintenance and repairs of the equipment installed in the chamber.

Hence the following conditions must be met:

$$\sum_{i=1}^n F_{nos} = \min, \sum_{i=1}^n Q_{nos} = \min, \quad (1)$$

where $\sum_{i=1}^n F_{nos}$ is the total surface area of the reduction chamber, m^2 ; $\sum_{i=1}^n Q_{nos}$ are the total heat

loss from the reduction chamber to the environment, Watt.

The comparison of the configuration of the chamber in the form of a cylinder and in the form of a parallelepiped with a square base, considering the minimum dimensions of the structure, showed that the total surface area of the configurable cylindrical chamber was $1.87 m^2$, and for the configuration in the form of a parallelepiped is $2.38 m^2$, which is more by 21.5 %. Hence an underground reduction chamber with a cylindrical configuration is recommended.

2. Thermal interaction of the underground reduction chamber with the environment. Mathematical modeling of the process of heat exchange between the underground chamber and the soil massif is in Fig. 1.

The temperature field of the reducing chamber is represented by linear heat sources $q_k^1, q_k^2, \dots, q_k^n$ placed along the axis y at some distance from each other Δ . The distance from any source q_k^m to the surface of a semi-bounded array can be given by the expression:

$$h_m^k = (h_{npus}^k - h_{k.p.}) + \Delta \cdot m, \quad \Delta = \frac{h_{k.p.}}{n+2}, \quad (2)$$

where h_{npus}^{κ} is the reduced depth of the chamber considering there is a snow cover (additional layer) in the wintertime, m [5]; $h_{\kappa.p.}$ is the height of the underground reduction chamber, m; Δ is the length of the step between the heat sources, m; m is the step number, on the axis y in the direction from the camera cover to the line source; n is the number of sources.

Fig. 1. Scheme of the problem of heat exchange between the reducing chamber and the soil massif

The temperature field of the soil forms the temperature values on the chamber contour: at the point E — $t_{h_{npus}^{\kappa}-h_{\kappa.p.}}$; at the point G — $t_{h_{npus}^{\kappa}}$; at the point F — $t_{h_{npus}^{\kappa}-h_{\kappa.p.}/2}$.

While implementing the mathematical model, the following boundary conditions were met:

— the temperature on the surface of the additional layer is equal to that of the outside air, i.e.,

$$t = t_{нап.в.};$$

— on the surface of an extra layer $y=0$; $0 \leq x \leq r_{\kappa}$;

— in the soil massif at $y \rightarrow \infty$ и $x \rightarrow \infty$, $t = t_{ecm}(y)$.

The expressions for identifying the temperatures on the cylindrical part of the chamber at point E , point F , point G and the bottom of the chamber, point P , point N form a system of n linear equations:

$$\left. \begin{aligned} \Delta t_E = t_{\kappa} + t_{ecm}(y) &= \frac{1}{2\pi\lambda} \sum_{i=1}^n q_{\kappa}^i \ln \frac{\sqrt{x_E^2 + ((h_{npus}^{\kappa} - h_{\kappa}) + \Delta \cdot m + y_E)^2}}{\sqrt{x_E^2 + ((h_{npus}^{\kappa} - h_{\kappa}) + \Delta \cdot m - y_E)^2}}; \\ \dots\dots\dots \\ \Delta t_N = t_{\kappa} + t_{ecm}(y) &= \frac{1}{2\pi\lambda} \sum_{i=1}^n q_{\kappa}^i \ln \frac{\sqrt{x_N^2 + ((h_{npus}^{\kappa} - h_{\kappa}) + \Delta \cdot m + y_N)^2}}{\sqrt{x_N^2 + ((h_{npus}^{\kappa} - h_{\kappa}) + \Delta \cdot m - y_N)^2}}. \end{aligned} \right\} \quad (3)$$

Under the condition $n \rightarrow \infty$, the system of equations implements the temperature distribution law on the chamber body. The amount of heat lost by the reduction chamber through a closed surface of an arbitrary shape is equal to the algebraic sum of the heat absorbed by the soil massif.

$$q_k^1 + q_k^2 + q_k^3 + q_k^\kappa + \dots + q_n^\kappa = 0. \quad (4)$$

The implementation of the mathematical model for the thermal interaction of the reduction chamber and the surrounding soil massif (2—4) given the assumptions and limitations, is presented in detail in [8]. As a result of the model implementation, the temperatures on the contour of the underground reduction chamber and the total heat losses were obtained (table 1).

Table 1

Distribution of the temperatures at the investigated points

Climatic zone of operation	Temperatures on the contour of the reduction chamber, °C					Heat losses in the reduction chamber, Watt/m ²
	т. E	т. F	т. G	т. P	т. N	
Cold	−20.7	−11.8	−8.1	−7.9	−7.7	115.58
Moderately warm	−4.2	−0.3	+2.05	+1.99	+1.97	50.5

As seen from table 1, a considerable change in the temperature along the height of the chamber leads to a decrease in that of the soil massif as it approaches the soil surface. On the bottom of the chamber, a relative constancy of temperature is observed, the temperature difference in the center of the base and on the circumference does not exceed 4.9 %. The heat losses through the walls and bottom of the underground chamber lead to a decrease in the temperature of the reduced gas in the pressure regulator, which increases the likelihood of condensate falling out and its freezing in the throttling organ of the regulator.

3. Development of an economic and mathematical model for optimizing the thickness of the thermal insulation of the underground reduction chamber. In order to minimize heat losses from the underground reduction chamber to the environment, an economic and mathematical model was developed for optimizing the thermal protection of the chamber and the ascending part of the vapor phase pipeline from the soil heat exchanger. As the objective function of the task, capital investments were taken in the construction of heat-insulated elements of the system for the complex: the ascending part of the vapor phase pipeline — the reduction chamber. As the investments in the construction of the elements of the vapor phase

pipeline and the reduction chamber of the isolated and non-insulated options are identical, only the variable part of the capital investments associated with a change in the thickness of the thermal insulation is considered:

$$K = K_{\text{в.ч.}} + K_{\text{к.р.}} = \min, \quad (5)$$

where $K_{\text{в.ч.}}$, $K_{\text{к.р.}}$ are the capital investments in thermal insulation of the ascending part of the vapor phase pipeline and the reduction chamber, rub.

In accordance with expression (5), the capital investments in the thermal insulation of the corresponding elements of the gas supply system can be represented as:

$$K_{\text{в.ч.}} = K_{\text{му}}^{\text{в.ч.}} + K_3^{\text{в.ч.}}, \quad (6)$$

$$K_{\text{к.р.}} = K_{\text{му}}^{\text{к.р.}} + K_3^{\text{к.р.}}, \quad (7)$$

where $K_{\text{му}}^{\text{в.ч.}}$, $K_{\text{му}}^{\text{к.р.}}$ are the capital investments in the thermal insulation of the ascending part of the vapor phase pipeline and the reduction chamber, rub.; $K_3^{\text{в.ч.}}$, $K_3^{\text{к.р.}}$ are the capital investments in the protective coating of the thermal insulation of the ascending part of the vapor phase pipeline and the thermal insulation of the reduction chamber, rub.

In its turn, the elements of the capital investments included in formulas (6), (7) are identified as follows:

$$K_{\text{му}}^{\text{в.ч.}} = \frac{\pi c_{\text{му}}}{4} \left((d_{\text{му.в.ч.}}^{\text{нар}})^2 - (d_{\text{зу.в.ч.}}^{\text{нар}})^2 \right) l_{\text{в.ч.}}, \quad (8)$$

$$K_3^{\text{в.ч.}} = c_3^{\text{в.ч.}} \pi d_{\text{му.в.ч.}}^{\text{нар}} l_{\text{в.ч.}}, \quad (9)$$

$$K_{\text{му}}^{\text{к.р.}} = \frac{1}{4} \pi c_{\text{му}} \left[\left((d_{\text{му}}^{\text{нар}})^2 - (d_{\text{зу}}^{\text{нар}})^2 \right) h_{\text{к.р.}} + 4(r_{\text{к.р.}}^{\text{вн}})^2 \delta_{\text{му}} \right], \quad (10)$$

$$K_3^{\text{к.р.}} = c_3^{\text{к.р.}} \pi d_{\text{му}}^{\text{нар}} h_{\text{к.р.}}, \quad (11)$$

where $c_{\text{му}}$ is the specific cost of thermal insulation, rub/m³; $l_{\text{в.ч.}}$ is the length of the ascending part of the vapor phase pipeline, m; $d_{\text{зу.в.ч.}}^{\text{нар}}$, $d_{\text{му.в.ч.}}^{\text{нар}}$ are the outer diameters of hydroinsulation and thermal insulation of the ascending section of the vapor phase, m; c_3 is the specific cost of a protective coating of thermal insulation, rub/m³; $d_{\text{зу}}^{\text{нар}}$, $d_{\text{му}}^{\text{нар}}$ are the outer diameters of hydroinsulation and thermal insulation of the reduction chamber, m; $r_{\text{к.р.}}^{\text{вн}}$ is the inner radius of the base of the reduction chamber, m; $\delta_{\text{му}}$ is the thickness of the thermal insulation, the upper and lower base of the reduction chamber, m.

The condition which prevents the thickness of the thermal insulation from rising are heat losses in the elements of the autonomous gas supply system, which are taken equal to the total

additional heating of the vapors of the propane-butane mixture obtained in the ground heat exchanger:

$$\varphi = \Delta Q = \sum_{i=1}^2 Q_{n.m.} - Q_{\text{д.н.}} = 0, \quad (12)$$

where $Q_{n.m.}$ are heat losses, Watt; $Q_{\text{д.н.}}$ is the total additional heating of vapors in the ground heat exchanger given by [9], Watt.

The analysis of expression (12) shows that the condition is possible if the heat losses of the system sections are equal and the additional heating is obtained. This equality will be fulfilled in the presence of thermal insulation of sites, i.e., $\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}$. In order to identify the optimal value of the objective function (5) for a given constraint (12), it was examined to the extremum using the Lagrange multiplier method for functions of n variables.

Let us present the investments in the thermal insulation of sections of the system as:

$$K = f(\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}). \quad (13)$$

Given expression (12), the Lagrange function is written as follows:

$$F(\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}) = f(\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}) + \mu \varphi(\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}), \quad (14)$$

where μ Watt is the Lagrange multiplier.

The essential conditions for the minimum function of the capital investments in the insulation of the vapour phase pipeline are formed as a system of equations with unknown $\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}$:

$$\begin{cases} F'(\delta_{mu}^{6.u.}) = 0, \\ F'(\delta_{mu}^{k.p.}) = 0, \\ \varphi(\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}) = 0. \end{cases} \quad (15)$$

The values $\delta_{mu}^{6.u.}, \delta_{mu}^{k.p.}$ defining the minimum of the objective function (5) for a given constraint (12) are optimal. The objective function (5—15) and the constraint (12) form an economic-mathematical model of the task. In order to identify the minimum of the objective function, the method of variant calculations was employed. Given the number of values $\delta_{m.u.}$ according to equations (8—11), the outer diameter of the insulated sections of the gas supply system and the values of $K_{6.u.}$ and $K_{k.p.}$ is identified. In compliance with [7] in the relevant areas heat losses are identified. Fulfillment of condition (12) will define the optimal thickness of thermal insulation of the studied sections of the system, and thus the minimum capital investment $K_{\min}$ in the thermal insulation. In order to numerically implement the economic-mathematical model (5—15), the corresponding calculations were conducted. The following initial data were used in the calculations.

1. The outdoor air temperature was taken in the climatic zones of operation: cold zone (Irkutsk), moderately warm (Krasnodar);
2. The gas consumption of the facility was 2.58 kg/h;
3. The temperature of the vapour phase at the entrance to the ascending section was taken according to the results of the calculation in the software [9];
4. The dimensions of the chamber were taken as a height of 0.5 m, diameter 0.7 m, wall thickness 0.08 m;
5. The thermal conductivity of *Aeroflex FIRO* $\lambda_{m.u.} = 0.03$ Watt/(m·K). The results of the calculations are shown in the graphs (Fig. 2 and 3).

Fig. 2. Identifying the capital investments in the construction of thermal protection of the ascending part of the steam phase pipeline and the reduction chamber (the cold climatic zone)

The analysis of the graphs revealed that the value of the minimum capital investment K_{min} as well as the corresponding optimal thermal insulation thicknesses on the ascending part of the steam phase pipeline $\delta_{mu}^{g.u.opt}$ and reduction chamber $\delta_{mu}^{k.p.opt}$ for the climatic zones of operation are:

- the cold one: $K_{min} = 8856$ rub.; $\delta_{mu}^{g.u.opt} = 0.023$ m, $\delta_{mu}^{k.p.opt} = 0.077$ m;
- moderately warm: $K_{min} = 7978$ rub.; $\delta_{mu}^{g.u.opt} = 0.014$ m, $\delta_{mu}^{k.p.opt} = 0.069$ m.

For practical implementation of the results as the generalized values of optimum thicknesses of thermal insulation for all the climatic zones of operation it is recommended that we accept $\delta_{mu}^{\delta.u,opt} = 0.023$ m, $\delta_{mu}^{\kappa.p,opt} = 0.077$ m. The above values correspond to the minimum of the capital investments in the conditions of the cold climatic zone and lead to overspending of capital investments by no more than 10 % in the conditions of the moderately warm climatic zone.

Fig. 3. Identifying the capital investments in the construction of thermal protection of the ascending part of the steam phase pipeline and the reduction chamber (the moderately warm climatic zone)

4. Modeling wet gas throttling in the pressure regulator of the underground reduction chamber. As noted above, the most unfavorable conditions for the operation of the gas supply system are those during the wintertime which are described by low ambient air and soil temperatures. Numerous research has shown that hydrates of liquefied hydrocarbon gas are formed by the contact of the steam phase and water in free form. This being the case, there is an area of propane hydrates formation in the temperature range from 0 to +5.5 °C, and butane hydrates from 0 to +1 °C [1, 4, 12]. In the area with negative temperatures, there are ice plugs occurring on the condition that the steam of the liquefied hydrocarbon gas is completely saturated with moisture and in the process of throttling with decreasing temperature and pressure, moisture is released in free form.

The criterion for evaluating the likelihood of hydrates occurring is the moisture content of the gas. If the actual moisture content of LPG at a given temperature is less than the maximum W_{max} , free moisture is not released during throttle flow, there is no solid phase in the throttling body of the regulator [1, 2].

Otherwise at $W_n(t) > W_{max}$ in the throttled flow, free moisture is released, which, under certain conditions, results in a solid phase. Its nature (ice and hydrate crystals) is defined by the temperature and pressure of the liquefied gas. According to the studies [11, 12, 17], free water in the liquid and vapor phases of LPG freezes at negative temperatures. Free water in the liquid phase of LPG at positive temperatures remains in the liquid state, and in the steam phase (at the certain temperature and pressure) forms crystal hydrates.

Moisture content of the steam phase of LPG $W_n(t)$ depending on the temperature of the throttled flow t is given by the equation:

$$W_n(t) = \frac{P_{H_2O}(t)}{P(t)}, \quad (16)$$

where $P_{H_2O}(t)$, $P(t)$ is the maximum elasticities of water steam and propane-butane steam at the certain temperature t , MPa.

According to Raoul, the relationship between temperature and pressure of the propane-butane mixture in the saturated state establishes the following equation:

$$P(t) = P_{np}(t)\Psi_n + P_{\bar{o}}(t)(1 - \Psi_n), \quad (17)$$

where $P_{np}(t)$, $P_{\bar{o}}(t)$ is the pressure of saturated steams of propane and butane at the certain temperature; Ψ_n is the molar content of propane in the steam phase of LPG.

According to the ratios [12, 15, 14], the pressure and temperature of hydrocarbons are given by the expressions:

$$P_{np}(t) = 10^{A_{np} - \frac{B_{np}}{C_{np} + t}}, \quad (18)$$

$$P_{\bar{o}}(t) = 10^{A_{\bar{o}} - \frac{B_{\bar{o}}}{C_{\bar{o}} + t}}, \quad (19)$$

where A_{np} , B_{np} , C_{np} , $A_{\bar{o}}$, $B_{\bar{o}}$, $C_{\bar{o}}$ are the empirical coefficients for propane and butane [3].

Certain calculations were conducted in order to calculate the wet gas throttling parameters.

The following initial data were considered in the calculations:

- the component composition of the steam phase of 90 % propane and 10 % butane;
- the temperature of the liquefied gas prior to throttling was taken based on the results of the computer calculations [9].

The results of the calculations are given in Table 2.

Table 2

Initial and final moisture content in the process of throttling the steam phase of propane-butane
in the pressure regulator of the underground reduction chamber

Temperature, $^{\circ}\text{C}$		Moisture content, mole %		Mass of the component, g			Moisture content, weight composition %		
$t_n^{H_2O}$	t_n^{KOH}	$W_n^{H_2O}$	W_n^{KOH}	$G_n^{H_2O}$	G_n^{KOH}	G_n^{max}	$W_n^{H_2O}$	W_n^{KOH}	W_{max}
Moderately cold climatic zone of operation									
-7.47	-10	0.08	0.256	1.44	4.612	5.0	0.0316	0.1	0.11
Cold climatic zone of operation									
-14.2	-20	0.06	0.1	1.08	1.8	2.0	0.024	0.04	0.045

As can be seen from Table 2, the throttling of the LPG steam phase is accompanied by an increase in the moisture content of the gas during reduction in the underground LPG chamber in any climatic zone of operation. This being the case, the final moisture content of the steam phase following throttling is less than the maximum one, the release of free water from the steam phase is not observed, which makes it unlikely for ice and hydrate plugs to form. Based on the above, it can be concluded that the reduction of the steam phase of LPG in the superheated saturated state occurs as the moisture content increases without water being released in free form. Hence the use of an underground reducing chamber provides hydrate-free reduction of the steam phase in any climatic zone of operation of the gas supply system.

Conclusions

1. As a result of the research, the configuration of the LPG reduction chamber with underground placement in the form of the cylindrical concrete well providing the minimum total surface participating in heat exchange with environment has been set forth and tested.
2. An economic-mathematical model for optimizing the thermal protection of the ascending part of the steam phase pipeline and the reduction chamber has been developed. As a result of the implementation of the model, the optimal thicknesses of thermal insulation were identified and recommended for use in any climatic zone of operation for the ascending section of the steam phase pipeline 0.023 m, for the underground reduction chamber 0.077 m.
3. According to the results of the modeling of the LPG steam phase throttling process in pressure regulators, the process occurs as the moisture content increases. This being the case, wa-

ter is not released in free form, which indicates that there is no ice and hydrate plugs in the pressure regulators during the throttling of steams in the underground reduction chamber.

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