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Justification of Gas Supply System based on Tank Units with Natural Regasification of Liquefied Hydrocarbon Gas, Preventing Formation of Hydrates in Pressure Controllers

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Abstract: Justification of gas supply system is given which prevents formation of crystalline hydrates in pressure controllers during operation of tank units with natural regasification of Liquefied Hydrocarbon Gas (LHG). Processes of heat exchange between gas supply system and ambiance are reviewed and their operating temperature conditions are determined. Prerequisites are formed to determine optimum thickness of thermal insulation of gas supply system elements which allows to ensure maintenance of superheat of vapor phase of liquefied hydrocarbon gas upstream pressure controller and avoid hydrate formation.

Key words: Liquefied hydrocarbon gas, tank unit, ground heat exchanger, prevention of hydrate formation, pressure controller, justification

INTRODUCTION

Research results represented in researches of various researchers by Nikitin and Krylov (1974) and Osipova *et al*. (2010) testify that operation of "subsurface tank-gas-distribution plant" gas supply system without moisture crystallization is ensured at any superheating of vapor phase of liquefied gas including minimum possible superheating which forms objective prerequisites for hydrateless operation related to tank units with natural regasification of Liquefied Hydrocarbon Gas (LHG). Schematic diagram of recommended gas supply system implementing the principles of hydrateless operation is given in Fig. 1.

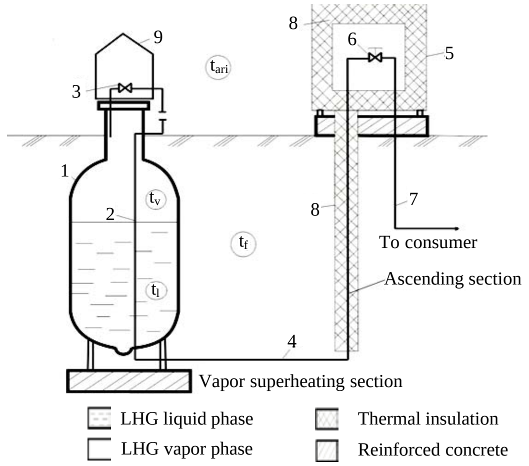

Fig. 1: Schematic diagram of liquefied gas supply from subsurface tank unit with vapor superheating in ground tube heat exchanger: 1) Subsurface tank; 2) Pipeline of LHG vapor phase; 3) Valve; 4) Ground tube heat exchanger; 5) Cabinet-type gas-distribution plant; 6) Pressure controller; 7) Low pressure gas pipeline; 8) Thermal insulation and 9) Tank head

The schematic diagram is operating as follow: LHG vapor phase is extracted from subsurface tank 1 with vapor phase pipeline 2 and supplied to ground heat exchanger 4 fabricated of steel pipe laid along the outline of tank unit foundation pit. The pipeline is insulated with 2 mm thick polymer film for corrosion protection. In order to isolate the ground heat exchanger during repair works, the valve 3 located in tank head 9 is used. In ground heat exchanger, LHG vapor phase is superheated using natural heat of soil mass. Superheated vapors enter cabinet-type gas-distribution plant 5 through ascending section of ground heat exchanger. Reducing unit of cabinet-type gas-distribution plant 6 is completed on the basis of gas equipment of cabinet-type gas-distribution plant GRPSh-6 with integral safety relief valve, safety shutoff valve and filter. After passing the reducing unit, LHG vapor phase enters customer's pipeline 7. In order to decrease heat loss and subsequently to prevent cooling of superheated

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gas ascending section of ground heat exchanger and cabinet for reducing unit are covered with heat insulating material 8.

In order to select proper thickness of insulating layer, heat exchange between ground and vapor phase of liquefied gas shall be researched in following elements of proposed scheme: subsurface tank, ground heat exchanger and cabinet-type gas-distribution station.

MATERIALS AND METHODS

The task of thermal interaction between liquefied hydrocarbon gas and ground is stated in mathematical formulation as following system of equations.

Differential equations of temperature patterns: In metal wall of a tank:

$$\frac{\partial^2 t_w}{\partial r^2}+\frac{1}{r}\times\frac{\partial t_w}{\partial r}+\frac{\partial^2 t_w}{\partial y^2}=0 \qquad (1)$$

In corrosion resistant insulation of a tank:

$$\frac{\partial^2 t_{ins}}{\partial r^2}+\frac{1}{r}\times\frac{\partial t_{ins}}{\partial r}+\frac{\partial^2 t_{ins}}{\partial y^2}=0 \qquad (2)$$

In frozen zone of ground:

$$\frac{\partial^2 t_f}{\partial r^2}+\frac{1}{r}\times\frac{\partial t_f}{\partial r}+\frac{\partial^2 t_f}{\partial y^2}=0 \qquad (3)$$

In melted zone of ground:

$$\frac{\partial^2 t_m}{\partial r^2}+\frac{1}{r}\times\frac{\partial t_m}{\partial r}+\frac{\partial^2 t_m}{\partial y^2}=0 \qquad (4)$$

Boundary conditions: At inner surface F_{boil} of a tank operating in LHG boiling mode:

$$\alpha_{boil}\left(t_{F_{boil}}-t_l\right)=\lambda_w\frac{\partial t_w}{\partial n}\bigg|_{n_{F_{boil}}} \qquad (5)$$

At inner surface F_{cond} of a tank operating in LHG condensation mode:

$$\alpha_{cond}\left(t_{F_{cond}}-t_v\right)=\lambda_w\frac{\partial t_w}{\partial n}\bigg|_{n_{F_{cond}}} \qquad (6)$$

At ground surface F_{gr}:

$$\lambda_f\left(\frac{\partial t_f}{\partial y}\right)_{y=0}=\frac{t_{surf}-t_{air}}{\frac{\delta_{sn}}{\lambda_{sn}}+\frac{1}{\alpha_{air}}} \qquad (7)$$

From which the thickness of additional ground layer equivalent to thermal resistance of snow cover and heat transmission into outside air:

$$H_{add}=\frac{\lambda_f}{\lambda_{sn}}\delta_{sn}+\frac{\lambda_f}{\alpha_0} \qquad (8)$$

In soil mass at $y\rightarrow\infty$; $r\rightarrow\infty$:

$$t(y)=t_e(y) \qquad (9)$$

Coupling equation: Between metal wall and corrosion resistant insulation of the tank:

$$\lambda_w\frac{\partial t_w}{\partial n}\bigg|_{n_{F_w}}=\lambda_{ins}\frac{\partial t_{ins}}{\partial n}\bigg|_{n_{F_{ins}}} \qquad (10)$$

Between corrosion resistant insulation and frozen ground:

$$\lambda_{ins}\frac{\partial t_{ins}}{\partial n}\bigg|_{n_{F_{ins}}}=\lambda_f\frac{\partial t_f}{\partial n}\bigg|_{n_{F_f}} \qquad (11)$$

Between frozen and melted zones of ground:

$$\lambda_f\frac{\partial t_f}{\partial n}\bigg|_{n_{ph}}=\lambda_m\frac{\partial t_m}{\partial n}\bigg|_{n_{ph}} \qquad (12)$$

Equation of tank thermal balance:

$$\int_{F_{boil}}\lambda_w\frac{\partial t_w}{\partial n}\bigg|_{n_{F_{boil}}}=\int_{F_{cond}}\lambda_{cm}\frac{\partial t_w}{\partial n}\bigg|_{n_{F_{cond}}}+K\left(F_{sc}+F_{fl}\right)\times\left(t_l-t_{air}\right) \qquad (13)$$

Following letter designation are used in Eq. 1-13:

t_f, t_m = Temperature of frozen and melted zones of ground
t_{ins}, t_w = Temperature of corrosion resistant insulation and metal wall of a tank
t_{Fboil} = Inner surface temperature of a tank operating in LHG boiling mode
t_{Fcond} = Inner surface temperature of a tank operating in LHG vapor condensation mode
t_l = Temperature of LHG liquid phase

t_v = Temperature of LHG vapor phase
t_{surf} = Surface temperature of soil mass
t_{air} = Air temperature
$t_n(y)$ = Natural distribution of ground temperature
α_{boil} = Coefficient of heat transfer from tank inner surface to liquid phase in LHG boiling mode
α_{cond} = The same for LHG vapor condensation
α_{air} = Coefficient of heat transfer from snow cover to air
λ_f, λ_m = Thermal conductivity of frozen and melted ground
λ_{ins}, λ_w = Thermal conductivity of corrosion resistant insulation and metal wall of a tank
λ_{sn} = Thermal conductivity of snow cover
K = Heat transfer coefficient of surface neck section and flange
y, r = Coordinates
n = Normal to iso metric surface
δ_{sn} = Snow cover thickness
F_{sc} = Surface of land neck section
F_{fl} = Surface of reducing head Flange

Explanations developing content of Eq. 1-13 and implementation of relevant mathematical model are presented in published researches by Kuznetsov and Kuritsin (2012), Osipova *et al.* (2010) and Shamin (1997).

During implementation of mathematical model 1-13, temperature values were obtained in design points of tank surface for following initial data:

- Subject of research vertical subsurface tank for liquefied gas with volume of 0.96 m^3
- Climatic region of tank unit operation cold-temperate zone
- Snow cover Height in the area of tank unit $H_{sn} = 0.25$ m
- Heat conductivity of snow $\lambda_{sn} = 0.35$ W/(m.K)
- Coefficient of heat transfer from ground surface to external air $\alpha_0 = 23$ W/(m.K)
- Soil characteristic in the area of tank unit: loam with density of p = 1793 kg/m^3 and heat conductivity of $\lambda = 1.29$ W/(m.K)
- Evaporation capacity of tank unit G = 0.25 m^3/h
- Liquefied gas temperature in design points of tank surface is $t_l = -1.93$°C

In order to verify adequacy of theoretical values obtained, experimental research was conducted. Commercial prototype of vertical subsurface tank for liquefied gas with volume of 0.96 m^3 was used as an object of experimental research. Experiment was implemented in natural regasification mode of liquefied gas composed of: 93.8% propane, 6.2% butane at 60% level of tank filling with gas and at constant vapor extraction value 0.25 m^3/h. Gas flow rate was measured with GSB-400 gas meter. Liquefied gas temperature in the tank and ground temperature was measured with TL-4 exhaust temperature gages with scale division value of 0.1°C. Temperature gages for measuring of LHG temperature were located in special metal pockets, provided by design of experimental plant. The pockets were located at tank neck flanges 0.03 m, at top tank head 1.1 m, at the half of tank height 2.2 m and at bottom tank head 2.3 m. Natural temperature of ground at different depth levels was measured at the distance of 6 m from tank center line in special pockets made of vinyl plastic tubes buried in soil mass for 0.5, 1, 2, 3, 4 m.

Test modes were selected, considering features of theoretical model of thermal interaction of “tank-ground” system as much as possible and evaluating maximum accuracy of initial prerequisites (existence of own temperature pattern of soil mass, inhomogeneity of boundary conditions on inner surface of the tank, quasi steady task definition): tests were conducted upon expiry of weekly period with the tank filled with liquefied gas up to maximum level 85% in the mode of natural dynamics of filling level, soil temperature and other influencing parameters. Such prerequisite to the experiment is conditioning maximum effect of instability of thermal processes of operating temperature modes of the tank unit.

The following parameters are measured during experiment: temperature of liquefied gas in the tank, external air temperature and natural temperature of soil at different levels were measured hourly for 7 days, then measured values were averaged.

RESULTS AND DISCUSSION

Results of experimental research are shown in Table 1. Analysis of Table 1 shows that in spite of significant external air temperature fluctuation and effect of instability of thermal processes in soil mass, operating temperature modes of the tank are sufficiently stable for a long period of time 7 days and longer. Deviations of current temperature values from their average values is not exceeding 1°C. This circumstance allows to consider unsteady thermal process in tank-soil system as consecutive change of quasi steady thermal conditions, i.e., it confirms initial methodical prerequisite assumed during development of mathematical model.

Table 1 shows that experimental temperature values of liquefied hydrocarbon gas in the tank are t_l from -1.7 to -1.8°C for design value $t_l = -1.93$°C with 12% maximum inaccuracy.

Hence, developed mathematical model of heat exchange between subsurface tank of liquefied gas and ground is adequately reflecting heat exchange features for

Table 1: Summary table of experimental data

	Temperature of liquefied gas in the tank (°C) at depth (m)					Temperature of soil mass (°C) at depth (m)				
No. of the test	3.3	2.2	1.1	0.3	Temperature of external air (°C)	4.0	3.0	2.0	1.0	0.5
1	-1.4	-1.30	-1.10	-1.20	-1.60	5.90	3.90	2.20	-0.10	-1.90
2	-1.4	-1.40	-1.40	-1.80	-2.50	6.00	4.10	2.60	-0.30	-1.60
3	-1.7	-1.60	-1.60	-1.80	-9.40	5.40	4.10	2.40	-0.80	-1.20
4	-2.0	-1.50	-1.60	-1.60	-11.40	5.80	4.00	2.50	-0.40	-1.90
5	-1.3	-1.50	-1.60	-2.00	-11.70	6.00	3.80	2.80	-0.30	-1.40
6	-1.8	-2.10	-2.40	-2.00	-11.20	5.90	4.50	2.90	-0.60	-1.40
7	-2.3	-2.50	-2.30	-2.30	-13.20	5.90	4.30	2.50	0.10	-2.20
In average during period	-1.7	-1.70	-1.71	-1.81	-8.71	5.87	4.01	2.56	-0.48	- 1.66

Table 2: Operating temperature modes of liquefied gas tank unit with vapor superheating in ground tube heat exchanger

Temperature of soil mass (°C) at depth of ground heat exchanger location		Temperature of vapor phase LHG (°C) in elements of gas tank unit						
			Vapor superheater of heat exchanger		Ascending section of heat exchanger		Cabinet-type GDS	
In natural condition	With accounting of heat influence of the tank	Underground tank	Inlet	Outlet	Inlet	Outlet	Inlet	Before pressure controller
+2.03	+0.62	-8.63	-8.63	+0.52	+0.52	-2.77	-2.77	-8.63

storage and regasification of hydrocarbon gas in subsurface tank units which allows to recommend it for extensive use in engineering calculation practice.

Research of heat exchange between liquefied gas vapor lines and soil is conducted with division of complicated complicated thermal engineering problem into four interconnected subproblems in accordance with tank unit diagram presented in Fig. 1:

- Heat exchange at vapor superheating section of subsurface pipeline
- Heat exchange at ascending section of subsurface pipeline
- Heat exchange at ascending section of surface pipeline
- Heat exchange in cabinet-type gas-distribution station

Finite-difference method is used to solve the problems. Initial prerequisites and solution algorithms are detailed in published researches by Kuritsin *et al.* (2011) and Osipova *et al.* (2010). For numerical implementation of proposed mathematical models, following calculations are conducted. Following initial data is used in calculations:

- Climatic region of tank unit operation cold-temperate zone
- Geometric volume of subsurface liquefied gas tank is $V = 0.96$ m^3
- Consumption of vapor phase from the tank $G = 1$ kg/h
- Thermal Capacity of vapor phase $C = 0.47$ (W.h)/(kg.K)
- Technical specification of ground heat exchanger seamless steel pipe with 26×3 mm diameter with 2 mm thick polymer tape waterproofing layer with heat conductivity of $\lambda_{ins} = 0.174$ W/(m.K)
- Laying depth of superheating section of ground heat exchanger $h_{sh} = 2.9$ m
- Superheater pipeline is laid along the outlines of the tank unit with Radius $R_{sh} = 1.9$ m
- Thermal insulation material of ascending section of ground heat exchanger and cabinet-type Gas-Distribution Station (GDS) polyurethane foam, heat conductivity $\lambda_{ins} = 0.019$ W/(m.K)
- Outside Diameter of thermal insulation of ascending section of ground heat exchanger $d_{vpu,\, ins} = d_{vnu,\, ins} = 0.1$ m
- Outside Diameter of heat insulated cabinet-type GDS $D_{out} = 0.5$ m
- Inside Diameter of heat insulated cabinet-type GDS $D_{in} = 0.3$ m

Results of relevant calculations are shown in Table 2. Table 2 shows the laying of ground heat exchanger along the outlines of typical tank unit foundation pit ensures superheating of LHG vapor phase from -8.63 to +0.52°C or for 9.15°C. Maximum possible superheating is 2.03-(-8.63) = 10.66°C.

Thereby, actual superheating value is 86% of its maximum. Further, increase of superheating level requires significant increase of foundation pit dimensions and superheating section length which increases capital investment in construction of tank unit and is economically unjustified.

Study of heat exchange processes between ground and vapor phase of liquefied gas in elements of proposed scheme: subsurface tank, ground heat exchanger ascending section of heat exchanger and cabinet-type gas-distribution station allowed to justify superheating of vapor phase of liquefied hydrocarbon gas and define required prerequisites for selection of required thickness of insulating layer of vertical (ascending) section of ground tube heat exchanger and cabinet-type gas-distribution station.

Capital investment in construction of heat insulated elements of LHG vapor line for complex: ascending section of ground heat exchanger cabinet-type GDS is defined as objective function of the problem:

$$K = K_{asc} + K_{GDS} = \min \tag{14}$$

Based on Eq. 14, following type objective function of the problem was formed:

$$K = f\left(\delta_{ascjns}, \delta_{GDSins}\right) = \min \tag{15}$$

Where:

$\delta_{asc, ins}$ = Thickness of thermal insulation at ascending section of ground heat exchanger (m)
$\delta_{GDS, ins}$ = Thickness of thermal insulation of a cabinet (m)

Control parameters of objective function were interconnected with following limitation:

$$\Delta t_{v, asc} = f\left(\delta_{asc, ins}\right) \tag{16}$$

$$\Delta t_{v, GDS} = f\left(\delta_{GDS, ins}\right) \tag{17}$$

In turn:

$$\Delta t_{v, asc} + \Delta t_{v, GDS} = t^{fin}_{v, sh} - t_v \tag{18}$$

Where:

$\Delta t_{v, asc}$, $\Delta t_{v, GDS}$ = Differential temperature of LHG vapor phase at ascending section of ground heat exchanger and in cabinet-type GDS
$t^{fin}_{v,sg}$ = Final temperature of vapor phase at the outlet of superheating section of ground heat exchanger (°C)
t_v = Temperature of saturated vapor at the outlet of feed tank (°C)

Objective Eq. 15 and limitations Eq. 16-18 form mathematical economic model of the problem. Variants calculation method is used to find minimum value of objective function.

Being defined by a number of values of $\delta_{asc, ins}$, outside diameter of heat insulated pipeline $d_{asc, ins}$ is determined. In accordance with mathematical model of heat exchange at ascending section of ground heat exchanger, temperature of LHG vapor phase was determined at the inlet of cabinet-type gas-distribution station $t^{init}_{v, GDS} = t^{fin}_{v, in}$. Then, at specified inlet temperature of a pressure controller $t^{fin}_{v, GDS} = t_v$, outside diameter of heat insulated cabinet D_{out} and required thickness of cabinet thermal insulation $\delta_{GDS, ins}$ was determined.

Optimum thickness of thermal insulation at ascending section of ground heat exchanger δ^{opt}_{ascins} and optimum thickness of thermal insulation of cabinet-type GDS $\delta^{opt}_{GDS, ins}$ correspond to version with minimum capital investment K_{min}.

For numerical implementation of proposed mathematical model, following calculations are conducted. Determination of optimum parameters of thermal insulation was conducted for cold, cold-temperate and warm operating climatic zone. Following initial data is used in calculations:

- Geometric Volume of subsurface liquefied gas tank is $V = 0.96$ m^3
- Ground heat exchanger seamless steel pipe with 26×3 mm diameter with 2 mm thick polymer tape waterproofing layer with heat conductivity of $\lambda_{ins} = 0.174$ W/(m.K)
- Laying depth of superheating section of ground heat exchanger $h_{sh} = 2.9$ m
- Superheater pipeline is laid along the outlines of the tank unit with Radius $R_{sh} = 1.9$ m
- Thermal insulation material of ascending section of ground heat exchanger and cabinet-type gas-distribution station polyurethane foam, heat conductivity $\lambda_{ins} = 0.019$ W/(m.K)
- Inside Diameter of heat insulated cabinet-type gas-distribution station $D_{in} = 0.3$ m
- Vapor phase temperature in subsurface tank $t_v = -8.63$°C
- Liquefied Gas consumption $G = 1.0$ kg/h
- Thermal Capacity of LHG vapor phase $c = 0.47$ W.h/(kg.K)

Results of calculations conducted are shown in Table 3. When forming gas supply system based on tank

Table 3: Values of thermal insulation thickness of system elements

	Thickness of thermal insulation (m) at climatic zone of gas tank unit operating			
Name of section	Very cold	Cold	Cold-temperate	Warm-temperate
Ascending section of heat exchanger	0.074	0.070	0.065	0.063
Cabinet-type GDS	0.099	0.090	0.084	0.082

units with natural regasification of liquefied hydrocarbon gas preventing formation of crystalline hydrates in pressure controllers, it is recommended to cover ascending section of ground heat exchanger and cabinet-type gas-distribution station with effective thermal insulation with thickness determined by Table 3 in order to maintain superheating of LHG vapor phase.

CONCLUSION

In order to prevent hydrate formation in pressure controllers during operation of tank units with natural regasification, diagram of liquefied gas supply from subsurface tank unit with vapor superheating in ground tube heat exchanger is proposed. Based on the analysis of processes of heat exchange between elements of gas supply diagram and ambiance, their operating temperature modes are defined which allow to determine maximum possible vapor phase superheating equal to 10.66°C.

Thickness values of thermal insulation of ascending section of ground heat exchanger and cabinet-type gas-distribution station of gas supply system are determined which provide maintenance of LHG vapor phase superheating upstream pressure controller, depending on operating climatic zone of tank unit.

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