Autonomous Gas Fuel Supply Systems with Natural Regasification of Liquefied Hydrocarbon Gas: Principles of Providing Gas Fuel to Customers

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Subject of study: Autonomous gas supply systems utilizing liquefied hydrocarbon gas serve as a prospective alternative to centralized gas supply systems based on piped natural gas. At the same time, such systems are very expensive, thus deterring their widespread application for gasification of remote settlements, single households, private farms and seasonal facilities. It is possible to reduce the cost of autonomous systems by implementing systems with natural regasification of liquefied natural gas. However, such systems have limited evaporation capacity of gas phase restricting its supply during maximal gas consumption periods.

A possible solution of the problem is using the autonomous gas supply systems placing reservoirs under the ground so that they utilize the warmth of the underground for re-gasification. In addition, the inclusion of the underground evaporator next to the reservoir in the system of the autonomous gas supply guarantees regeneration of the steam phase for various compositions of gas, even in case of a high concentration of butane. The study considers a joint work of the underground reservoir and underground evaporator maintaining a constant gas supply to the building, even during the periods of the peak gas consumption.

We propose developing autonomous gas supply system that supports continuous gas supply for a facility by utilizing natural re-gasification of liquefied natural gas

Materials and methods: we have summarized results of many research papers on natural regasification of liquefied natural gas and used mathematical simulations and primary principles of heat exchange theory in order to develop a schematic of such system.

Results: We propose a schematic of autonomous gas supply systems (for individual customers) that utilizes natural evaporation of liquefied hydrocarbon gas and supports continuous gas generation due to joint operation of service tank and ground evaporators.

Conclusions: The proposed structure of autonomous gas supply system that combines steam generation phase in service tank and ground heat exchanger helps to provide continuous gas supply for customers without using additional energy carriers to evaporate liquefied hydrocarbon gas.

We also provide recommendations on practical application of research data obtained during our studies.

1. Introduction

Independent gas supply systems are a sound alternate to piped natural gas systems. Deficiency of well-developed piped gas supply should not influence comfort conditions for people and lower their living standards. Independent gas supply systems maintain desired level of comfort including cooking, hot
water supply and dwellings heating. At the same time arrangement of such systems requires sound approach to their structural design. Liquid butane, propane or propane and butane can be used as liquefied hydrocarbon gas (LPG). The usage of a certain composition of gas depends on system operational conditions.

When using independent gas supply systems completed with land storage tanks, LPG with the predominant content of propane should be used. At the same time if gas supply system is designed for frigid climate or very frigid climate, even propane does not provide for gage pressure in the tank and therefore a vapor phase supply to consumers is not guaranteed [1, 2].

Underground installation of tanks is needed for gage pressure generation in the tank. Upon that, the ground is a natural heat source which provides for a vapor phase generation in the supply tank and gage pressure generation in the tank [1, 2, 3].

Steam output of LPG tank depends on many parameters such as: tank capacity, wetted surface area, disengagement area, gas blend composition and gas use conditions [4, 3].

Intensive consumption of vapor phase in maximum gas use conditions leads to its decline under steam-relieving area due to the deficient generation in the tank. Upon that, steam blanket pressure under steam-relieving area is reduced and riches a critical value of gas supply shut-off valve reaction and gas supply is cut off. For increase in productivity of vapor phase of gas supply system the use of ground heat exchanger is provided, which allows to avoid condensation of vaporized vapor phase when transporting to consumers and capability of additional generation of a vapor phase as a result of vaporization of liquid LPG in the ground heat exchanger itself.

Scientists Kuritcin B.N., Usachev A.P., Sotnikova O.A., Pavlutin M.V., Maksimov S.A., Chendorain M. [5, 6, 7, 8, 9, 3, 10] researched supply through the use of ground heat exchangers. In the above mentioned studies ground heat exchangers were considered irrespective of underground gasholders operational conditions, and this in significant extent changes initial operation conditions of the last ones. The studies were confined to selection of the required steam output of elements of the heat exchanger horizontal part with disregard for environmental influence at the time of the next gas pressure reduction and supply to consumers.

Simultaneous operation of the tank and the ground heat exchanger is considered in the study [11]. At the same time the research was conducted only for vertical LPG tanks with periodic vapor phase withdrawl from the tank, because the tank has only liquefied hydrocarbon gas vapor phase connections. During periods of heavy gas consumption (weekends and public holidays) steam capacity of the underground tank subject to natural regasification does not provide for estimated gas consumption of gas supply objects which leads to gas supply system breakdown. To rectify these deficiencies the scheme of independent gas supply system is provided (Figure 1).

Independent gas supply system works in the following manner. Steam mixture of propane and butane is generated in the tank through natural regasification LPG executed due to the heat exchange between the underground tank and the ground, remains balanced under overpressure emerged due to LPG liquid phase contents. At first stage, propane and butane steam mixture is withdrawn to consumers through the vapor phase 2 pipeline.

Valve position 5 relative to the steam mixture path is open. Vapor phase while moving through independent gas supply system, comes into the ground heat exchanger 4, where the gaseous mixture is additionally heated due to the heat exchange with ground mass. Further, steam mixture is delivered to pressure regulator 6, where reduces its pressure and is piped to consumers (through pipeline 8). In the course of propane and butane steam mixture withdrawal from the tank 1, the pressure under disengagement surface is reduced; when pressure reaches the value of 69 kPa, the valve 5 shuts down, the pressure rises, the liquid phase from the tank moving along the liquid phase pipeline is delivered to ground heat exchanger 4, where it begins to vapor and in the form of a vapor it is delivered to pressure regulator 6. In the course of vaporizing liquefied hydrocarbon gas the pressure in the tank begins to rise under disengagement surface, the valve 5 cuts off the liquefied gas flow, and the tank natural steam capacity is becoming used. Thus, the scheme provides for a steady gas supply even with heavy gas consumption. The condensate collector 9 serves to collect condensate and unevaporated heavy
residues. Condensate is emptied through the liquid removal tube twice a year.

![Diagram of gas supply system](image)

**Figure 1.** Scheme of autonomous gas supply system with natural regasification: 1 – underground tank; 2 – vapor phase pipeline; 3 – liquid phase pipeline; 4 – ground heat exchanger; 5 – valve; 6 – pressure regulator; 7 – heat insulation of gas supply system elements; 8 – low pressure pipeline; 9 – condensate collector with purging tube; 10 – heat-insulated letdown station chamber.

Heat insulation 7 section of the gas supply system allows to provide for the stable temperature of steam mixture of propane and butane gas when the mixture moves along the system elements being adjacent to surrounding air, snow cover and frozen ground, and to keep the superheat of steam mixture in the heat exchanger through to the heat-insulated letdown station chamber 10. Position of the pressure regulator 6 in heat-insulated chamber 10 allows to reduces the cooling of the vapor phase and conduct the reduction of the superheated mixture of propane and butane vapors delivered into the regulator under an elevated temperature, and to prevent formation of hydrates and ice plugs in the process of propane and butane steam mixture reduction in the regulator [12].

In addition, the inclusion of the ground heat exchanger next to the reservoir in the system of the autonomous gas supply guarantees regeneration of the steam phase for various compositions of gas, even in case of a high concentration of butane.

The study proposes mathematical model describing consumers gas supply technology using the above mentioned scheme [9].

Superheat of the LPG vapor phase is carried out in a ground heat exchanger. The calculation scheme is shown in Figure 2.
The amount of heat obtained from the ground mass to the heat exchanger is calculated by the formula:

\[
Q_{\text{pvp}}^{\text{htex}} = \frac{(T_{\text{vp}} - T_{\text{gr}}) \pi d_{\text{htex}}^{\text{ext}}}{\alpha_{\text{int}} d_{\text{htex}}^{\text{int}} + \frac{1}{2\lambda_m} \ln \frac{d_{\text{htex}}^{\text{ext}}}{d_{\text{htex}}^{\text{int}}} + \frac{1}{2\lambda_{\text{wp}}} \ln \frac{d_{\text{wphtex}}^{\text{ext}}}{d_{\text{wphtex}}^{\text{int}}} + \frac{1}{\alpha_{\text{ext}} d_{\text{wphtex}}^{\text{ext}}}},
\]

(1)

Where \( T_{\text{vp}} \) – inlet heat exchanger temperature of vapor phase, (K); \( T_{\text{gr}} \) – ground temperature, (K); \( d_{\text{htex}}^{\text{ext}} \) – length of horizontal section of vapor phase pipeline, (m); \( \alpha_{\text{int}} \) – coefficient of heat transfer from internal environment to metal wall, (W:\cdot m^{-2} \cdot K^{-1}); \( \lambda_m \) - metal heat conduction, (W:\cdot m^{-1} \cdot K^{-1}); \( \lambda_{\text{wp}} \) - hydro-proofing insulation heat conduction, (W:\cdot m^{-1} \cdot K^{-1}); \( d_{\text{htex}}^{\text{int}}, d_{\text{htex}}^{\text{ext}} \) – inner and outer diameter of ground heat exchanger, (m); \( d_{\text{wphtex}}^{\text{int}}, d_{\text{wphtex}}^{\text{ext}} \) – inner and outer diameter of hydro-proofing insulation of ground heat exchanger, (m); \( \alpha_{\text{ext}} \) – coefficient of the heat transfer from the outer surface of hydro-proofing insulation of the ground heat exchanger to the ground mass, (W:\cdot m^{-2} \cdot K^{-1}).

The amount of heat received by handled medium over the ground exchanger depending on gas consumption of an object is determined by the formula:

\[
Q_{\text{sh}} = 0.278 e_m G \Delta t_{\text{sh}},
\]

(2)

Where \( e_m \) – heat capacity of vapor phase of propane and butane mixture, (kJ:\cdot kg^{-1} \cdot K^{-1}); \( G \) – amount of liquefied gas flowing from the tank in the ground heat exchanger, (kg:\cdot h^{-1}); \( \Delta t_{\text{sh}} \) – value of gas heating due to heat input from the ground mass, (K).

Equating the expressions (1) and (2), we evaluate the vapor phase heating. If we know the initial temperature value, we deduce the final value at the end of the ground heat exchanger section. The problem is solved by the method of successive approximations. In the same manner we calculate the change in temperatures of the liquid phase of propane and butane mixture in the ground heat exchanger.

Let us take the following as initial data:
- vapor phase pipeline of ground heat exchanger with the diameter of 0.04 (m) and hydro-proofing insulation thickness of 4 (mm);
- heat conduction of metal wall of the vapor phase pipeline – 45 (W:\cdot m^{-1} \cdot K^{-1}) [13];
- coefficient of heat transfer from liquefied hydrogen gas to the pipeline inner surface and outer surface of pipeline hydro-proofing insulation to the ground mass, $\alpha_{\text{int}} = 8 \, (\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1})$; 
- ground temperature for the frigid zone 265 (K); for cold-temperature zone 269.9 (K); 
- amount of liquefied gas flowing from the tank in the ground heat exchanger, 2.58 (kg-h$^{-1}$); 
- heat capacity of vapor phase of propane and butane mixture, 1.55 (kJ-kg$^{-1}$-K$^{-1}$); 
- ground heat exchanger inlet temperature of gaseous propane and butane mixture $T_{\text{vp}}$ is assumed on the basis of the research findings [11]. 
Calculation data is displayed in the Table 1. 

| Ground heat exchanger       | Ratio of components in propane / butane gas mixture, % | Temperature values in climatic zones of operation, K |
|-----------------------------|---------------------------------------------------------|-----------------------------------------------------|
|                             |                                                        | $T^\text{ext}_{\text{vp}}$ | $T^\text{end}_{\text{vp}}$ | $T^\text{ext}_{\text{vp}}$ | $T^\text{end}_{\text{vp}}$ |
| moving the vapor phase      | 90/10                                                   | 251.41                | 259.15                | 259.21                | 265.88                |
|                             | 65/35                                                   | 252.91                | 260.03                | 260.74                | 266.88                |
|                             | 20/80                                                   | 252.32                | 259.65                | 261.4                 | 267.31                |
| moving the liquid phase     | 90/10                                                   | 257.08                | 264.49                | 250.3                 | 258.3                 |
|                             | 65/35                                                   | 257.72                | 264.91                | 251.83                | 259.33                |
|                             | 20/80                                                   | 258.35                | 265.32                | 251.79                | 259.3                 |

Conclusion: 
1. The scheme of independent gas supply system of liquefied hydrocarbon gas combining the usage of underground tank with the ground heat exchanger and allowing providing consumers with gas supply of any gas consumption, was performed. 
2. The calculations confirming the possibility of overheating of the vapor phase in the ground heat exchanger are carried out. 
3. The changes in temperatures in the ground heat exchanger allowing providing the vapor phase reduction without hydrates formation in the pressure regulator, were detected. 

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