Modeling and studying basic parameters of tank sets in combined regasification

N N Osipova, S S Kuznezov, A V Rulev
Building Heat and Gas Supply, Ventilation, Water Supply and Applied Hydro-Gas Dynamics, Yuri Gagarin State Technical University of Saratov, 77, Politechnicheskaya street, Saratov 410054, Russia

E-mail: nautech@inbox.ru

Abstract. This paper proposes switching tank sets to combined regasification so as to reduce the energy consumption in artificial regasification systems. To that end, a tank set must be equipped with a special valve to sustain a pressure of 0.135 MPa in vapor blankets. This valve will trigger alternating draft of liquid and vapor phases of liquefied petroleum gases so as to maximize the utilization of the natural evaporating capacity of feed tanks.

To make the proposed solution scientifically sound, the research team has developed a mathematical model of combined regasification of liquefied petroleum gases, which integrates the two basic periods of tank-set operation: natural regasification in the feed tank, and artificial gasification in the evaporator. In order to validate the proposed model, a pilot set was used for experimentation. The obtained experimental data correlate well with the numerical output of the proposed model, making it recommendable for engineering practice.

Studies show that implementing combined regasification in liquefied gas tanks will considerably reduce the energy costs of evaporating gas, making the liquefied gas supply systems much more energy-efficient and cost-effective.

1. Introduction

In the today’s Russian and international practice, gas supply to housing and industrial sites remote from central energy supply facilities makes increasing use of decentralized gas supply systems for users to get propane-butane mixtures of liquefied petroleum gases (LPG) from tank sets [1-7]. When using liquefied petroleum gases as the main fuel in tank-based systems, such gases are subject to forced (artificial) evaporation in evaporators with an intermediate solid or liquid heat transfer medium that sustains natural convection [8-11]. It is important to switch tank sets to combined regasification so as to reduce the energy consumption in artificial regasification systems. Combined regasification is named so because it combines two basic tank operation periods: natural regasification of liquefied gas in the feed tank; and subsequent artificial regasification of the LPG in the evaporator. The process makes use of the natural heat in the surrounding soil, as propane-butane mixtures, even rich in butane, can be partially evaporated in ground heat exchangers; however, the heat of the soil is not currently used for regasification of liquefied petroleum gases rich in butane [12-13]. In order to improve the energy efficiency of evaporators, this paper proposes equipping LPG sets with a special valve that will maintain the vapor pressure in the feed tanks at 0.135 MPa. This valve will maintain alternating draft of liquid and vapor phases of liquefied petroleum gases so as to maximize the utilization of the natural evaporating capacity of feed tanks [14,15]. When a certain minimum pressure threshold is reached, the
valve shuts close. The resulting pressure drop causes the liquid phase to move from the tank to the evaporator, i.e. triggers a forced (artificial) evaporation in a flow-through heat exchanger. Environmental heat causes the feed-tank LPG temperature and the vapor-phase pressure to rise. The valve opens again, the pressure behind it rises, the liquid phase is cut off, and the system switches to natural regasification. The cycle repeats.

2. Mathematical Modeling of LPG Regasification

To make the proposed solution scientifically sound, the research team has mathematically modeled combined regasification of liquefied gases.

For convenience, break the combined regasification problem into two interrelated subproblems, each pertaining to a particular tank-set mode.

2.1. Natural Regasification

Break the total duration of natural tank regasification $\tau_{\text{nat}}$ into $S$ estimated time intervals, each lasting $\Delta \tau$. Let $b$ be the onset and $e$ be the end of such estimated interval.

Assuming that at any point of any time interval $\Delta \tau$, the tank specifications alter insignificantly, the heat balance equation for the $i$th interval will be as follows:

$$
\left( K_{\text{nat}}^b F_{\text{mix,nat}}^b \left( t_s - \frac{t_{\text{nat}}^b + t_{\text{nat}}^e}{2} \right) - r G \right) \Delta \tau + \left( \frac{c_m M_{\text{m,nat}}^b + c_l M_{\text{l,nat}}^b}{t_{\text{nat}}^b + t_{\text{nat}}^e} \right) = 0,5 K_{\text{nat}}^b F_{\text{mix,nat}}^b \Delta \tau + c_m M_{\text{m,nat}}^b + c_l M_{\text{l,nat}}^b,
$$

where $K_i$ is the tank heat transfer coefficient, kJ/(h·m²·K); $F_{\text{mix,nat}}$ is the moistened surface area of the tank, m²; $t_i$ is the temperature of the LPG liquid phase in the tank, °C; $t_s$ is the natural soil temperature on the tank placement axis, °C; $c_m$, $c_l$ are the metal housing/liquefied gas mass heat capacities, kJ/kg·K; $M_{\text{m,nat}}$ is the metal housing mass corresponding to the moistened tank surface, kg; $M_{\text{l,nat}}$ is the mass of the liquid in the tank; $r$ is the heat of liquefied gas vaporization, kJ/kg; $G$ is the gas flow from the tank, kg/h.

After transformed, the equation (1) is written as follows:

$$
t_{\text{nat}}^i = \frac{\Delta \tau \left( K_{\text{nat}}^b F_{\text{mix,nat}}^b \left( t_s - \frac{t_{\text{nat}}^b + t_{\text{nat}}^e}{2} \right) - r G \right) + t_{\text{nat}}^b \left( \frac{c_m M_{\text{m,nat}}^b + c_l M_{\text{l,nat}}^b}{t_{\text{nat}}^b + t_{\text{nat}}^e} \right)}{0,5 K_{\text{nat}}^b F_{\text{mix,nat}}^b \Delta \tau + c_m M_{\text{m,nat}}^b + c_l M_{\text{l,nat}}^b},
$$

The equation (2) is implemented by an iterative method sequentially for each time interval; for algorithm, see [16].

2.2. Combined Regasification

As the tank reaches the design pressure $P_{\text{comb}}$, the valve closes partially, and the evaporator starts receiving cooled liquid phase of the LPG. Further tank-set operation involves combined regasification: the vapor phase is partially generated by the evaporator ($G_v$); the remainder, $G_p$, is generated by the feed tank that draws heat from the soil.

Since both the vapor phase and the liquid phase of the LPG are drawn, the mass of the liquefied gas in the tank has a corresponding fluctuation $M_i$, which in its turn alters other process parameters: the liquefied gas tank fill level $\varphi$, the moistened tank surface area $F_{\text{mix}}$, the tank mass $M_m$, and the tank heat transfer coefficient $K$.

Drawing the vapor from the tank alters the composition of the liquid LPG phase, as it becomes richer in butane. Since the tank vapor blanket pressure $P_{\text{comb}}$ is constant, such changes in the liquid-phase composition alter the temperature $t_l$.

Break the total duration of combined tank regasification $\tau_{\text{comb}}$ into $S$ estimated time intervals, each lasting $\Delta \tau$. 

2
Assuming that over any time interval $\Delta \tau$, the tank specifications alter insignificantly, the heat balance equation for the kth interval will be as follows:

$$K_{comb}^{b}F_{init,comb}^{b}\left(t_{k} - t_{comb}^{l} + t_{comb}^{r}\right)\Delta \tau + (c_{m}M_{w,comb}^{b} + c_{m}M_{L,comb}^{b})\left(t_{comb}^{l} + t_{comb}^{r}\right) = rG\Delta \tau,$$  \hspace{1cm} (3)

The equation (3) is implemented by an iterative method sequentially for each time interval; for algorithm, see [16].

The total gas produced by the natural evaporating capacity of the tank can be found for natural/combined regasification by the formula:

$$M_{nat} = G\tau_{nat} + \sum_{i=1}^{S} G_{p}\Delta \tau + \sum_{i=1}^{T} G_{p}\Delta \tau.$$  \hspace{1cm} (4)

The natural evaporating capacity of the tank contributes to the total vapor generation of the tank set:

$$Z = \frac{M_{nat}}{M_{l}^{0} (\varphi_{b} - \varphi_{out})},$$  \hspace{1cm} (5)

where $M_{l}^{0}$ - is the mass of gas in a 100% full tank; $\varphi_{b}, \varphi_{out}$ are the initial and the residual tank fill levels, %.

3. Experimentation

In order to validate the proposed model, a pilot set was used for experimentation. Liquefied petroleum gas was taken from a horizontal underground tank, 2.5 m$^3$ in volume. For research, LPG was drawn constantly at 3.0 m$^3$/h. The initial (binary) gas composition was as follows: 64.2% propane, 35.8% n-butane. The soil (loam) had the following thermophysical characteristics: density $\rho=1,793$ kg/m$^3$, humidity $\omega=12.22\%$, heat transfer coefficient $\lambda=1.3$ W/(m·°C) [17, 18].

The following parameters were measured during the experiment:

- pressure and temperature of the liquefied gas in the tank;
- experiment duration and gas flow;
- soil temperature along the tank placement axis;
- composition of the liquid LPG phase in the tank;

Excess gas pressure was measured by two Class 1.0 spring gauges limited at 0.6 and 0.1 MPa, respectively.

The temperature of the liquefied gas in the underground tank was measured by thermometers (0.1 °C per division, +20…-30 °C measurement limit). The soil temperature was measured by a thermometer placed at a depth of 1.1 m, 6 m away from the tank.

Thermometer temperature increase did not exceed 0.5°C per minute at a 30°C temperature drop between the thermometer mercury tank and the environment. Temperature and pressure measurements took place once a day, 4 times per session, 3 to 5 minutes between readings. Gas temperature and pressure would vary in this experiment from +18 to -27 °C and from 0.5 to 0.135 MPa, respectively.

Gas flow was metered by two SGB-G6 meters connected in series to control each other. Given the gas temperature and pressure before passing through the meters, their readings were recalculated to the reference. Gas flow was metered once an hour. A special valve was used to keep it constant.

Gas was sampled to test its composition every 20 to 30 hours. For sampling, the research team used special sampling cartridges, each being a pipe section with two valves on the ends. Before sampling, each cartridge was blown multiple times with the same gas. The liquid LPG phase was sampled from the tank via a tube, then fully evaporated in a water-heated coil and pumped into the sampler. To
minimize sampling error, five samplers were gas-filled every time. For chemical analysis, the research team used a chromatographer.

4. Results
Figures 1 and 2 show the results of experimental studies into the operating parameters of an underground tank subject to combined liquid/vapor phase draft; the results are shown as experimental points. Solid lines show the numerical output of the model.

The baseline was made up of the experimental tank-set parameters as measured at the onset of its operation. The design parameters of the underground tank, 2.5 m$^3$ in volume, as well as its specifications and heat transfer coefficient adjusted to the thermophysical properties of the soil were adopted from [19,20].

![Figure 1. Soil and LPG temperature as a function of experiment duration: 1 is the soil temperature, °C; 2 is the liquefied gas temperature, °C](image)

![Figure 2. LPG composition and pressure as a function of experiment duration: 1 LPG composition, mole fraction; 2 LPG pressure, MPa](image)

As can be seen from Figures 1 and 2, modeled values of these parameters are consistent with the experimental data. At a confidence probability of 0.95, maximum difference between theoretical and empirical data is:
- 16.4% for the liquefied gas temperature;
- 9.6% for the liquefied gas pressure;
- 9.1% for the liquefied gas components.

5. Conclusions.
The proposed mathematical model has been experimentally proven valid. It makes it recommendable for engineers. Theoretical and experimental studies show that the natural evaporating capacity of LPG feed tanks contributes significantly (up to 50-60%) to the total vapor generation of the tank set. In this regard, switching tank sets that use artificial regasification to combined LPG regasification will substantially reduce the costs of evaporating liquefied gas. The extra costs of installing of liquid/vapor phase switching valve pay off in a year.
References
[1] Treloar R D 2010 Gas installation technology. 2nd edition (John Wiley & Sons, Ltd.) p 498
[2] Saxon F 2006 Tolley’s basic science and practice of gas service (Gas service technology vol.1)
Newnes p 536
[3] Rachevsky B S 2009 Liquefied Petroleum Gases (Moscow: Neft i gas) p 640
[4] Wang X, Economides M 2009 Advanced natural gas engineering gulf publishing company p 368
[5] Osipova N N, Ryapisova Yu S, Bychkova I M 2016 Prospects for expanding the use of
liquefied petroleum gas in the russian federation p 207
[6] Guo-HuaShi Lu Aye Yan-Chen Liu Xian-Jun Du Dynamic simulation of liquefied petroleum
gas vaporisation for burners Applied Thermal Engineering 137 575–583
[7] Fedyaev A V, Lachkov G G 2017 Effectiveness of remote region boiler plant conversion to
liquefied petroleum gas from local fields Proceedings of Irkutsk State Technical University
10(129)
[8] Yakovlev A A, Chamchiyan Yu Ye 2017 Liquefied hydrocarbon production and use methods
Energetika, ekologiya, khimiya: collection of student papers (Ulyanovsk: UISTU) p 329
[9] Shevtsov S A, Kargashilov D V and Shutkin A N 2018 Fire and Explosion Safe Technology of
Storage and Regasification of Liquefied Petroleum Gas Chemical and Petroleum
Engineering 54(1-2) 38–40.
[10] Shevtsov S A, Kargashilov D V, Habibov M A U 2016 Peculiarities of designing tank sets for
liquefied petroleum gases for autonomous gas and energy supply in the context of fire risk
evaluation Pozharnaya bezopasnost 3(3) 150–155
[11] Ajeysurya S et al 2016 Hazop study in LPG installation in process industry Advances in Natural
and Applied Sciences 10.9 SE 149–153
[12] Usachev A P, Shurayts A L, Rulev A V, Usacheva T A 2010 Systemic study to intensify heat
exchange in LPG regasification units (Saratov: SSTU) p 210
[13] Usachev A P, Shurayts A L, Rulev A V 2013 Using the soil heat for the tank systems of gas
supply with artificial evaporation of the liquefied hydrocarbonic gas Vestnik SSTU 1(69)
148–152
[14] Kuritsyn B N, Osipova N N, Kuznetsov S S 2012 Combination regasification of liquefied
petroleum gas for cost-effective tank-based gas supply Proceedings of the 8th International
Conference (Prague) pp 108–111
[15] Kuritsyn B N, Kuznetsov S S 2012 Energy-Saving Tank-Based Liquefied Gas Supply Systems
Proceedings of the 25th International Research Conference (Saratov: SSTU) pp 333–335
[16] Kuritsyn B N, Osipova N N, Kuznetsov S S 2011 Development of a mathematical model for
liquefied petroleum gas combination regasification Vestnik SSTU 4(59) 218–224
[17] Agapkin V M, Krivoshein B L, YufinHeat V A 1981 Hydraulics calculations for oil and
petroleum product pipelines (Moscow: Nedra) p 256
[18] SP 25.13330.2012 2011 Soil bases and foundations on permafrost soils. Updated SNiP 2.02.04-
88 (Moscow: Ministry of Regional Development of Russia) p 126
[19] Nikitin N I 1976 Liquefied gas to fuel public utilities and agricultural facilities (Moscow:
Stroyizdat) p 105
[20] SP 62.13330.2011 2010 Gas distribution systems. Updated SNiP 42-01-2002 (Moscow:
Ministry of Regional Development of Russia) p 113