Calculation of electric energy savings and simulation of tank operation with variable extraction of steam and liquid phases of propane-butane mixtures

A V Rulev, S S Kuznezov and V O Sevostiyanov
Department of Heat and Gas Supply, Ventilation, Water Supply and Applied Hydro-Gas Dynamics, Yuri Gagarin State Technical University of Saratov, 77 Polytechnicheskaya street, Saratov, 410054, Russian Federation

E-mail: nautech@inbox.ru

Abstract. Currently, when consumers use various categories of propane-butane mixtures of liquefied petroleum gas as the main or backup energy carrier, natural and artificial regasification systems based on electric or direct fire evaporators with intermediate heat transfer agent or solid-state intermediate heat transfer agent of various evaporation capacity, which operate depending on the design in various evaporation modes, are widely used. An important element for reducing energy consumption in the artificial liquefied petroleum gas regasification systems is the switching of tank to the combined regasification mode. The combined cycle provides two main periods of tank operation: the initial period with natural regasification of liquefied gas in the day tank, ground tube evaporator, and the subsequent period with artificial regasification of the propane-butane mixture in the evaporator with an intermediate heat transfer agent. For the purpose of theoretical justification of the proposed cycle, a mathematical model of combined regasification of liquefied petroleum gases was developed, which comprehensively takes into account the main periods of tank operation: with natural regasification mode in the day tank, ground heat exchanger and artificial regasification mode in the evaporator. The results of the conducted research show that the implementation of the combined regasification cycle in the liquefied gas supply can significantly reduce the energy costs of its evaporation, increases the energy efficiency of liquefied petroleum gas supply systems and provides an average annual savings of 33.7% in electric energy for regasification.

1. Introduction
In modern domestic and foreign experience of gas power supply to houses and industrial facilities located remotely from the main power station, decentralized gas power supply systems fed with propane-butane mixtures (PBM) of liquefied petroleum gases (LPG) from tanks are increasingly used [1-6]. When using liquefied petroleum gases as the main energy carrier in gas tank systems, they are evaporated artificially in evaporators with an intermediate solid-state or liquid heat transfer agent, under conditions of its natural convection [7-10]. An important element for reducing energy consumption in systems of artificial liquefied petroleum gas regasification is the switching of tanks to the combined regasification mode. The combined cycle provides two main periods of tank operation: the initial period with natural regasification of liquefied gas in the day tank, ground tube evaporator and the subsequent period with artificial LPG regasification in the evaporator with an intermediate heat transfer agent. The natural regasification mode is possible due to the natural heat of the surrounding soil, when...
propane-butane mixtures, even with a high content of butane fractions, can be partially evaporated in the ground heat exchangers, but currently the heat of the soil mass is not used for the regasification of liquefied petroleum gas with a high concentration of butane fractions [11]. At the same time, electric energy is a more valuable energy carrier and is characterized by a higher cost compared to LPG used as fuel in direct fire evaporators [12].

In order to save heat for regasification, the principle and technical solution was justified, consisting in the evaporation of part of the liquid phase directly in the underground tank 2 (Figure 1), enclosed in a polymer case 3 filled with an inert low-boiling liquid and a flow ground evaporation pipeline 1 by using the natural heat of the soil with alternate supply of the steam and liquid phases to the evaporator using the phase switch valve 7.

![Energy saving diagram of an electric LPG evaporator](image)

**Figure 1.** Energy saving diagram of an electric LPG evaporator: 1 – ground tube evaporator; 2 – LPG steel tank; 3 – polymer case filled with antifreeze; 4,6 – liquid and steam phase tubes; 5 – sealed gasket; 7 – steam and liquid phase switching valve; 8 – low pressure control; 9 – tubular electric heaters; 10 – electric evaporator; 11 – evaporation coil; 12 – aluminum intermediate heat transfer medium.

According to the proposed method, during the initial period of operation, the steam phase from underground tank 2 (Figure 1) is fed through the steam stand pipe 6, then through steam and liquid phases selector valve 7 to evaporation coil 11, overheats in it, and then goes to the consumer through the output pipeline and low-pressure regulator 8.

When the pressure and temperature of the saturated steam phase in tank 2 decreases to the calculated value, valve 7 closes the steam phase supply through stand pipe 6 and opens the liquid phase supply to ground tube evaporator 1. The resulting pressure drop between tank 2 and evaporator 1 provides a rise of the liquid phase through the supply pipeline to ground tube evaporator 1, where it partially evaporates due to the heat of the soil to the dryness factor $X_s$ until the boiling point of the propane-butane mixture $t_{S,b}$ rises to a temperature close to the minimum temperature of the soil on the axis of its location $t_{S,min}$. The liquid phase not evaporated in ground evaporator 1 with dryness factor $X_s$ enters evaporation coil 9, where it is completely evaporated due to the heat supplied from the tubular electric heaters 9 through a layer of solid-state heat transfer agent 12. Due to the heat leak from the ground, the steam pressure in tank 2 increases, and valve 7 opens again. The gas is supplied to the consumers again by supplying the vapor phase from tank 2. The cycle is repeated. The proposed solutions provide for the use of a continuous-flow ground evaporator pipeline 2 located at the bottom.
of the pit around tank 1 at low gas flow rates (Option A, Figure 2). In cases of higher evaporation capacities, the principle of radial horizontal location of pipeline 2 is proposed, which is implemented on the basis of directional drilling of horizontal wells, followed by the installation of U-shaped pipe elements 3 in them (Option B, Figure 2).

![Figure 2. Options for continuous-flow ground evaporator pipeline.](image)

2. Materials and Methods
For the purpose of theoretical justification of the proposed cycle, a mathematical model of combined liquefied gas regasification was developed.

For the convenience of research, we divide the complex problem of combined regasification into two interrelated subtasks in accordance with the tank operation modes.

We divide the total duration of tank operation in the mode of natural regasification $\tau$ into $S$ calculated time intervals of duration $\Delta \tau$. $b$ means the beginning of the calculated time interval, and $e$ means the end of the calculated time interval.

Assuming that the tank technical characteristics change very slightly at the point of a separate time interval $\Delta \tau$, the heat balance equation for the $i$-th time interval is as follows:

$$K_i F_{mix,i} \left( t_s - \frac{t_{l,i} + t_{e,i}}{2} \right) \Delta \tau + \left( c_m M_{m,i} + c_{m,i} M_i \right) (t_{l,i} + t_{e,i}) = r G \Delta \tau,$$

where:
- $K_i$ is the tank heat transfer coefficient, kJ/(h·m²·K);
- $F_{mix,i}$ is the tank wetted surface, m²;
- $t_s$ is the temperature of the LPG liquid phase in the tank, °C;
- $t_{l,i}$ is the temperature of the natural ground soil on the axis of tank location, °C;
- $c_m, c_{m,i}$ is mass heat capacity of the metal shell and liquefied natural gas, kJ/kg·K;
- $M_{m,i}$ is the mass of the metal shell corresponding to the tank wetted surface, kg;
- $M_i$ is mass of liquid in the tank, kg;
- $r$ is heat of vaporization of liquefied gas, kJ/kg;
- $G$ is gas flow rate from the tank, kg/h.
After the transformations, equation (1) will be as follows:

\[
\tau \left( K_{mix,i} \left( \frac{t_i - t_i^b}{2} \right) - rG \right) + t_i^b \left( c_m M_{m,i} + c_m M_{l,i} \right) \\
0.5K_{mix,i} \Delta \tau + c_m M_{m,i} + c_m M_{l,i}
\]

\[
t_i^d = \frac{\Delta \tau}{0.5K_{mix,i} \Delta \tau + c_m M_{m,i} + c_m M_{l,i}}, \quad (2)
\]

Equation (2) is applied by iteration method sequentially for each time interval in accordance with the algorithm presented in [13].

The boiling point of PBM at the ground evaporation pipeline outlet is determined depending on the minimum temperature of the soil on the axis of its location \( t_{gr,min} \) (in March) by the formula:

\[
t_{e,s} = t_{s,min} - \Delta t_{min}, \quad (3)
\]

\( \Delta t_{min} \) – minimum temperature pressure in the ground liquefied gas system, \(^0\text{C}.\)

The proportion of the liquid phase numerically equal to the dryness factor that can be evaporated in a ground evaporation pipeline is determined by the known value of the boiling point of PBM at its outlet \( t_{e,s}.\)

\[
X_s = P_{mix} \cdot \left( \frac{\psi - \psi}{P_{mix} - 10 \psi - \psi - \psi} + \frac{1 - \psi}{P_{mix} - 10 \psi - \psi - \psi} \right)
\]

\[
\psi - \text{propane content in the liquid phase of the initial PBM, mol;}
\]
\( A_b, B_b, C_b, A_p, B_p, C_p \) – the weighted average coefficients for butane fraction and the propane within a certain range of temperatures.

**Figure 3.** Chart for determining the fractional amount of liquid phase \( X_s \) that can be vaporized in a ground evaporator pipeline.
The subsequent period of tank operation provides a combined regasification mode: the \( G_v \) evaporator generates a part of the steam phase, the day tank and the continuous-flow ground evaporator pipeline due to the heat leak from the surrounding soil generate the other part of \( G_p \).

The extraction of the steam and liquid phases of liquefied petroleum gas determines the corresponding dynamics of the mass of liquefied gas in the tank \( M_f \), which, in turn, causes changes in other technical parameters: the level of filling the tank with liquefied gas \( \varphi \), the tank wetted surface \( F_{\text{mix}} \), the mass of the tank \( M_m \), the heat transfer coefficient of the tank \( K \).

During the extraction of steams from the tank, the fractional composition of the LPG liquid phase changes, and the content of the butane fraction increases in it. Since the pressure of the steam blanket in tank \( P_{\text{comb}} \) is constant, the change in the fractional composition of the liquid phase is accompanied by an increase in its temperature \( t_l \).

We divide the total duration of tank operation in the combined regasification mode \( \tau_{\text{comb}} \) into \( T \) calculated time intervals of \( \Delta \tau \) duration.

Assuming that the technical parameters of the tank change very slightly during certain time intervals, the heat balance equation for the \( k \)-th time interval of tank operation in the combined regasification mode will be similar to equation (1).

The total amount of gas obtained due to the natural evaporation efficiency of the tank when the tank is operating in the natural and combined regasification modes is determined by the formula:

\[
M = G\tau + \sum_1^5 G_p \Delta \tau + \sum_1^7 G_p \Delta \tau .
\] (5)

The contribution of the natural evaporation efficiency of the tank to the total evaporation capacity of the tank is

\[
Z = \frac{M}{M_l^0 (\varphi_b - \varphi_{\text{out}})} ,
\] (6)

where:

\( M_l^0 \) is a mass of gas in the tank at 100\% filling, kg;

\( \varphi_b, \varphi_{\text{out}} \) is the initial and residual levels of filling the tank, \%.

Saving of electric energy for the LPG evaporation is defined as the ratio of the amount of heat obtained due to the natural evaporative capacity of an underground tank \( Q_n \) and a flow ground evaporator \( Q_{\text{gr}} \) to the total amount of heat energy required for evaporation of the calculated mass flow rate of gas \( G \).

\[
\Delta Q = \frac{Q_n + X_{gr} (Q_r - Q_{\text{gr}})}{Q_r} .
\] (7)

\( X_{gr} \) - the percentage of the liquid phase (dryness factor) that can be evaporated in the ground evaporation pipeline, unit fraction

The expanded formula for determining the amount of heat obtained by artificial heat supply is as follows:

\[
Q_a = (1 - X_{gr}) [(\xi_b - \xi_{r}) - (G_p \tau_{\text{cool}} + \xi_{al})][r + C_i (t_h (P_h) - t_e (P_p)) + C_v (t_h - t_e)] + \\
+ C_i [(G_p \tau_{\text{cool}} (t_h - t_{h,\text{cool}} (P_h) + t_{e,\text{cool}} (P_p)) / 2] + \xi_{al} (t_h - t_{e,\text{cool}} (P_p)) ,
\] (8)

where:

\( \tau_{\text{cool}} \) - duration of the LPG cooling period in the underground tank, h;
ξ, ξ, ξ – accordingly, the mass of the liquid phase at the beginning of the cooling period, before the next refueling and during the periods of alternate sampling of liquid and steam phases of LPG from the tank, kg;

C, C – accordingly, the averaged specific heat capacities of the liquid and steam phases of LPG, kJ/kg*K;

\( t_{\text{b,cool}}(P_b), t_{\text{e,cool}}(P_p) \) – accordingly, the temperature of the liquid phase of LPG at the beginning and end of the cooling period, °C;

\( P_b, P_p \) – pressure of saturated LPG vapors at the beginning and end of the cooling period, MPa;

\( t_b, t_e, t_h \) – respectively, the temperature of the beginning and end of the boiling of LPG and overheating of its vapors, °C.

To verify the reliability of the proposed mathematical model, field observation was conducted on an experimental unit. An underground tank with a volume of 2.5 m³ was used as a liquefied petroleum gas source. Studies were conducted with a constant extraction of LPG at 3.0 m³/h. The initial gas composition in terms of a binary mixture: propane - 64.2%, n-butane - 35.8%. Thermal characteristics of the soil (loam): density \( \rho = 1793 \text{kg/m}^3 \), humidity \( \omega = 12.22 \% \), thermal conductivity coefficient \( \lambda = 1.3 \text{ W/(m*°C)} \) [14].

3. Results

The results of experimental studies of operational parameters in an underground tank with combined extraction of the liquid and steam phases are presented in Figure 4 as data points. Figure 4 shows the results of numerical implementation of the mathematical model as solid lines.

Experimental values of parameters of the tank at the beginning of its operation were used as initial parameters for the calculation. The design parameters of the underground tank with a volume of 2.5 m³ and its technical characteristics, as well as the heat transfer coefficient, taking into account the thermal characteristics of the soil mass, were adopted from open data.

![Figure 4](image-url)  
**Figure 4.** Dependences of the temperature, component composition, and pressure of liquefied petroleum gas on the duration of the experiment: 1 - soil temperature, °C; 2 - component composition of LPG, mole fraction; 3 - LPG pressure, MPa; 4 - LPG temperature, °C.
As we see on Figure 4, the theoretical values of the studied parameters agree quite well with the experimental data. The maximum discrepancy between the theoretical and experimental values with a confidence probability of 0.95 is:

- by the liquefied gas temperature 16.4%;
- by liquefied gas pressure 9.6%;
- by the component composition of liquefied gas 9.1%.

Calculations performed using formulas (7) - (8) for the underground tank with a volume of 10 $m^3$ and an evaporator with a capacity of 32 kg/h located in a moderately cold climate area, for gas with a butane content of 75 mol.%, show that the application of the proposed scheme provides for at least 33.7% of the average annual savings in electrical energy for the LPG evaporation.

4. Conclusion
Methodological provisions were developed for the use of natural soil heat for regasification by evaporation of part of the liquid phase in a continuous-flow ground heat exchanger and an underground storage tank, which provides an average annual savings of 33.7% in electric energy for regasification. Experimental studies confirm the reliability of the proposed mathematical model. The results of theoretical and experimental studies show that the natural evaporation capacity of LPG day tanks makes a significant contribution to the overall evaporation capacity of tank. In this regard, the switching of tank with artificial regasification to the combined LPG regasification mode provides an adequate reduction in energy consumption for the liquefied gas evaporation. At the same time, the additional costs of installing the liquid and steam phase selection valve are compensated within 1 year.

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