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Justification of Operating Conditions for Gas Supply Systems Based on Cylinder Units of Liquefied Hydrocarbon Gas

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Abstract: Results of the study regarding the influence of climatic conditions on operating modes of cylinder units of Liquefied Hydrocarbon Gas (LHG) are provided. Conditions for use of external cylinder units are justified, process parameters for their operation with indoor location are determined. Recommended residual level of cylinder filling (24-33%) for use of gas for needs of cooking and hot water supply is determined which allows to ensure continuous gas supply, forming consumers' buffer stock in case of untimely delivery of cylinders due to organizational and technical reasons.

Key words: Liquefied hydrocarbon gas, cylinder units, gas consumption, residual filling level, gas buffer stock

INTRODUCTION

Portable and stationary cylinders with capacity of 1-80 L with gauge pressure up to 1.6 MPa are generally used today for gas supply to individual households and low-rise buildings, small public utility and industrial facilities and facilities of an agricultural nature. The cylinders with capacity of 27 and 50 L are prevailing. The latter will be located in a room where gas appliances are installed or in special outdoor cabinets.

For design of gas supply based on cylinder units, following recommended practices are generally adhered: cylinder with the capacity of 50 L ensures up to 30 days of gas supply to consumers, if gas is used for cooking process only, i.e., for operation of gas stove only. In this case it is assumed that cylinder gas is used by consumer completely and no residual level is envisaged (Klimenko, 1962; Staskevich,1986). Furthermore, in case of low residual level of gas in cylinder, natural evaporation capacity of the latter will not comply with design gas consumption. In this case, consumer is enforced to content oneself with less amount of gas, i.e., partial failure of gas supply system is observed. In some cases, especially at low temperatures of ambient air, gas evaporation in the cylinder is ceased and consumer can't receive gas for a certain time (complete failure of gas supply system).

Gas supply systems are socially important because they define the level of domestic convenience of people and industrial progress. Failure of gas supply system causes changes in schedule of work and rest of people, leads to psychological and social tension which affects health adversely and may have negative consequences. In this regard, supply of Liquefied Hydrocarbon Gas (LHG) cylinders to consumers shall be implemented with consideration for stability and safety requirements for operation of gas supply system.

MATERIALS AND METHODS

Features of geographic location of Russian territory characterized by significant differentiation of climatic conditions require improved approach to the issues of design and operation of gas supply systems. When selecting design solutions on issues of supplying with liquefied hydrocarbon gas, outdoor air temperatures in cold season play determinative role.

Elements of liquefied hydrocarbon gas supply systems (gas pipelines, cylinder and tank units, etc.) are not capable of retaining heat (heat accumulation), therefore, even short-term deviations of ambient temperature from design values may affect operating modes of gas supply systems considerably. Thereby, ambient temperature values for calculation should be selected considering its recommended reliability. It is recommended to assume reliability factor of design temperature conditions for engineering equipment systems of buildings and structures equal to K = 0.5-0.9. Therefore, actual ambient temperature may exceed design value not more than once per two years of operation of gas supply system (K = 0.5) or not more than once per 10 years of operation (K = 0.9).

Determinative condition of stable and safe operation of cylinder units is an excessive pressure of saturated

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vapor whose value depends on gas blend composition and ambient air temperature. Presence of excessive gas pressure in cylinders provides sufficient conditions for stable product regasification and supply of vapor phase to consumer.

Nominal operation of cylinder unit (at rated gas consumption by gas stove) is assumed as highest provision level of gas consumption. Presence of excessive pressure of 0.05 MPa in a vessel at LHG temperature equal to ambient air temperature (based on condition of reliable operation of pressure controller) is assumed as lowest provision level. At these conditions, cylinder unit does not ensure sufficient evaporation capacity but it ensures supply of certain minimum amount of gas to consumer, providing minimum gas consumption level.

In order to justify operating conditions of gas cylinder units, integrated stude was carried out, allowing to determine application for outdoor gas cylinder units, operating modes of cylinders for their installation inside facilities being provided with gas supply, residual level of cylinder filling with consideration for gas buffer stock. Methods of variants calculations, successive approximations and comparative analysis are used in the study.

RESULTS AND DISCUSSION

Results of the study for determination of operating conditions of gas cylinder units are shown on Fig. 1. The study was carried out with following initial presuppositions:

- Climatic zone of operation: very cold, cold, temperate cold, temperate warm
- Design temperatures of outdoor air with regard to climatic zone of operation and reliability factor of temperature conditions
- Composition of liquefied hydrocarbon gas: commercial propane and commercial propane-butane, commercial butane

As shown by the study carried out (Fig. 1) in cold and temperate-cold climatic zones, outdoor gas cylinder units don't ensure continuous gas supply in winter period even for minimum gas consumption level. In conditions of temperate-warm climatic zone, minimum gas consumption level is ensured if residual level of gas of 44-68% is present (depending on LHG composition and reliability of outdoor air temperature) which is unacceptable both in engineering and economic terms.

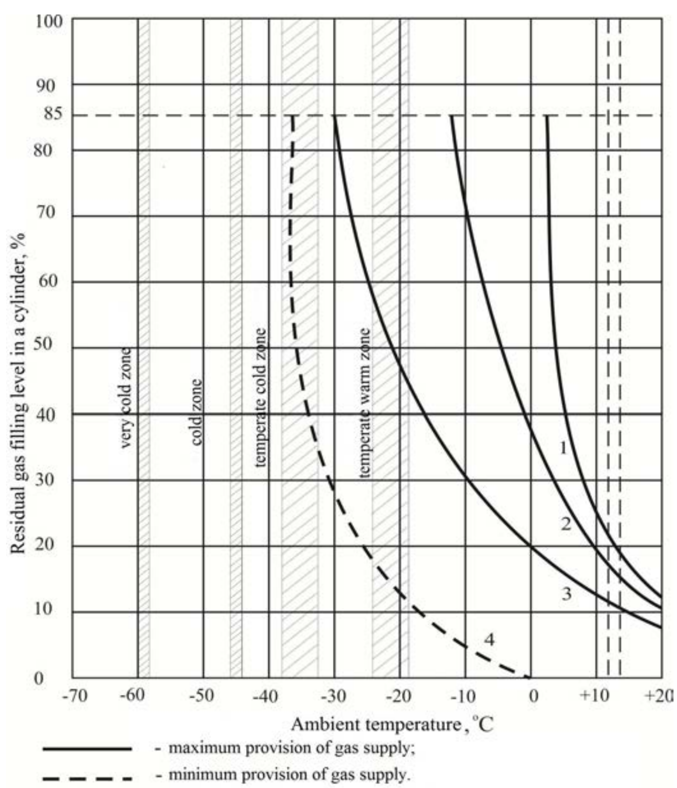

Fig. 1: Determination of operating conditions of outdoor gas cylinder units; 1: liquefied gas of commercial butan grade; 2: liquefied gas of commercial propane-butan grade; 3, 4: liquefied gas of commercial propane grade

Thereby, application field of outdoor gas cylinder units is the provision of gas supply to the temporary functioning facilities (holiday villages, summer tourist camps, seasonal agricultural industry enterprises, etc.) at positive ambient temperatures.

Installation of cylinders inside heated premises and their operation at positive ambient temperatures (+10°C and higher) will ensure minimum gas consumption at any residual gas level present. Furthermore, operation of gas cylinder unit with maximum provision of gas supply requires a justification of required residual gas level in cylinder. Natural regasification of liquefied gas in cylinder is conditioned by two factors:

- By means of decrease of internal energy of the system: liquid-metal
- By means of heat infiltration from environment above activity of temperature head: air-liquid phase of LHG

For long-term gas consumption with continuous vapor extraction, stationary operating temperature conditions of cylinder are observed. Heat consumed for evaporation (regasification) of LHG will be provided by means of heat infiltration from ambient air.

Design evaporation capacity of the vessel g, kg/h in conditions of stationary vapor extraction will be determined by the equation (Kuritsyn, 1988):

$$g = \frac{k \cdot F_{wet} \cdot (t_a - t_l)}{r} \quad (1)$$

Where:
- k = Heat transfer coefficient of a cylinder $W/(m^2 \cdot K)$
- F_{wet} = Wetted surface of a cylinder
- m^2; t_a = Ambient temperature
- °C; t_l = Temperature of liquefied gas in the vessel
- °C; r = Evaporation heat of liquefied gas (W·h/kg)

Wetted surface of a cylinder F_{wet} will be determined by the curve (Fig. 2), depending on value of residual level of gas filling before next filling.

In actual operating conditions of cylinder units, gas consumption has dynamic nature. Daily dynamics of gas consumption is observed on industrial and domestic facilities. It is conditioned by shift system of enterprises, specifics of use of gas equipment during gas consumption period. Gas consumption of residential buildings is distinguished by its extreme hourly irregularity. Generally, differential equation of thermal balance of cylinder unit is as follows:

$$k \cdot F_{wet} \cdot (t_a - t_l) \cdot d\tau - r \cdot g \cdot d\tau = \pm (c \cdot M_l + c_m \cdot M_m) \cdot dt_l \quad (2)$$

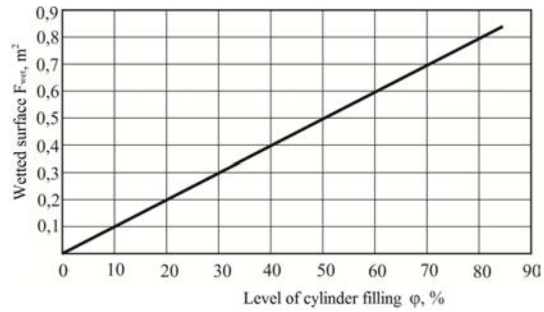

Fig. 2: Dependency of area of wetted surface of 50l cylinder on level of liquefied gas filled in

Where:
- dx = Differential time increment (h)
- dt = Differential temperature increment of liquefied gas (°C)
- c_m, c_l = Heat capacity per unit weight of metal shell of cylinder and liquid phase of LHG (W·h)/(kg·K)
- M_m, M_l = Weight of metal shell and liquid phase of LHG in cylinder (kg)

Daily dynamics of gas consumption causes corresponding dynamics of thermal operating modes of cylinder units. If the value of heat infiltration from environment is higher than heat consumption for regasification of LHG, right part of equation is assumed positive. Heat excess is accumulated by cylinder unit, raising internal energy of the system: liquid-metal. Temperature of LHG in the vessel is increasing.

If heat consumption for regasification of LHG is higher than heat infiltration value, right part of equation is assumed negative. Deficiency of heat for regasification of LHG will be compensated by decrease of internal energy of the system: liquid-metal. Temperature of LHG in the cylinder is decreasing.

Solution of Eq. 2 in such generalized formulation is absent in known literary sources. Certain solutions proposed by some authors describe individual cases of cylinder unit operation:

- Continuous vapor extraction mode g in conditions of stationary thermal state of the cylinder (Kuritsyn, 1988)
- Continuous gas consumption mode g for specified operating period of cylinder unit $\tau_{OT\tau}$ (Staskevich, 1986)
- Cyclic operation mode of gas cylinder unit, combined of gas consumption periods with permanent load g for a time period $\tau_{OT\tau}$ and periods of zero gas consumption (g = 0) for a time period τ_{nep} (Ivanova, 2005)

Although, specified modes may be observed in actual gas supply practice, they don't reflect the specifics of gas consumption in residential buildings. In this regard, implementation of Eq. 2 in generalized formulation is required for development of mathematical model of evaporation capacity of liquefied gas cylinder units.

Dividing total operation time of cylinder unit into a number of design time intervals with duration $\Delta\tau$, we can write the Eq. 2 in finite difference form. Then for j-th design interval for j = 1, 2, ..., n, we have:

$$[k_j F_{wet, j}(t_a - t_{l, j}) - rg_j]\Delta\tau = \pm(c_l M_{m, j} + c_m M_{m, j})\Delta t_{l, j} \quad (3)$$

Where:

- g_j = Design gas consumption in j-th operating interval of cylinder unit (kg/hour)
- $t_{l, j}$ = Average temperature of LHG liquid phase in the vessel in j-th interval of its operation (°C)

LHG temperature variation during j-th operating interval of cylinder unit is obtained from the Eq. 3:

$$\Delta t_{l, j} = \frac{k_j F_{wet, j}(t_a - t_{l,j}) - rg_j}{c_l M_{l, j} + c_m M_{m, j}} \quad (4)$$

LHG temperature in the end of j-th operating interval is obtained from equation:

$$t^k_{l, j} = t_{l, j} + \Delta t_{l, j} \quad (5)$$

Design parameters of cylinder unit in j-th operating interval k_j, $F_{wet, j}$, $M_{l, j}$, $M_{m, j}$ are determined by calculation for relevant level of vessel filling with liquefied gas φ_j. Level of vessel filling with liquefied gas in the end of j-th time interval is obtained from the equation:

$$\varphi^k_j = \varphi_j - \frac{g_j \Delta\tau}{\rho_l V} \quad (6)$$

Where:

- ρ = Density of liquid phase of LHG (kg m^{-3})
- V = Geometric volume of the vessel (m^3)

Assuming the values of parameters $t^k_{l, j}$ and φ^k_j in the end of jth time interval as average values for next j+1 operating interval $t_{l, j+1}$, φ_{j+1} the problem may be solved by step-by-step method. The following are defined as initial operating parameters of gas cylinder unit: $t_{l, 1} = t_a$; φ_1 = 85% (limit of vessel filling with liquefied gas as per safe operation requirements). Knowing the dynamics of level of vessel filling with liquefied gas φ_j, we can calculate the dynamics of LHG composition $\psi_{i, l, j}$ (for i = 1, 2, ..., m). Knowing LHG composition $\psi_{i, l, j}$ and its temperature $t_{l, j}$, liquid phase pressure dynamics in a cylinder $P_{wet, j}$ is calculated in accordance with algorithm described in Osipova *et al*. (2012).

Equation complex (2-6) represents the mathematical model of evaporation capacity of liquefied gas cylinder units. In comparison with solutions of other authors, the model proposed considers daily dynamics of gas consumption combined with heat accumulating capacity of cylinder units and reflects the specifics of gas consumption in residential buildings more adequately, providing use of additional evaporation capacity reserves. Solution of Eq 2-6 complex has shown that installation of cylinders with the capacity of 50 L inside the heated rooms and their operation at positive ambient air temperatures (+10°C and higher) provides operation of 4-burner gas stove with maximum provision of gas consumption for 22 day and 4-burner gas stove and water heater for 12 day.

In order to ascertain required residual gas level in cylinder with regard to operating mode of gas cylinder unit according to actual schedule of gas consumption in residential buildings, relevant study was carried out. Operation of gas cylinder unit according to actual schedule of gas consumption in residential buildings with regard to days with maximum gas consumption was accepted as design mode of gas consumption in residential buildings.

According to Kuritsyn (1988) and Klimenko (1962), maximum daily gas consumption by an apartment G^d_{max}, kg/day is determined by equation:

$$g^d_{max} = \frac{q^y_p S k^d_{max}}{365 \cdot Q^H_P} \quad (7)$$

Where:

- q^y_p = Yearly gas consumption per 1 person, accepted depending on gas equipment of the apartment (kJ/(man·year))
- S = Occupation density factor of the apartment (man/ap)
- k^d_{max} = Coefficient of daily gas consumption, accepted depending on gas equipment of the apartment
- Q^H_p = Calorific capacity of liquefied hydrocarbon gas (kJ/kg)

Individual gas cylinder unit with 50 L cylinder located in the kitchen of the apartment being provided with gas supply is accepted as an object of the study. Following initial data and presuppositions are used in calculations:

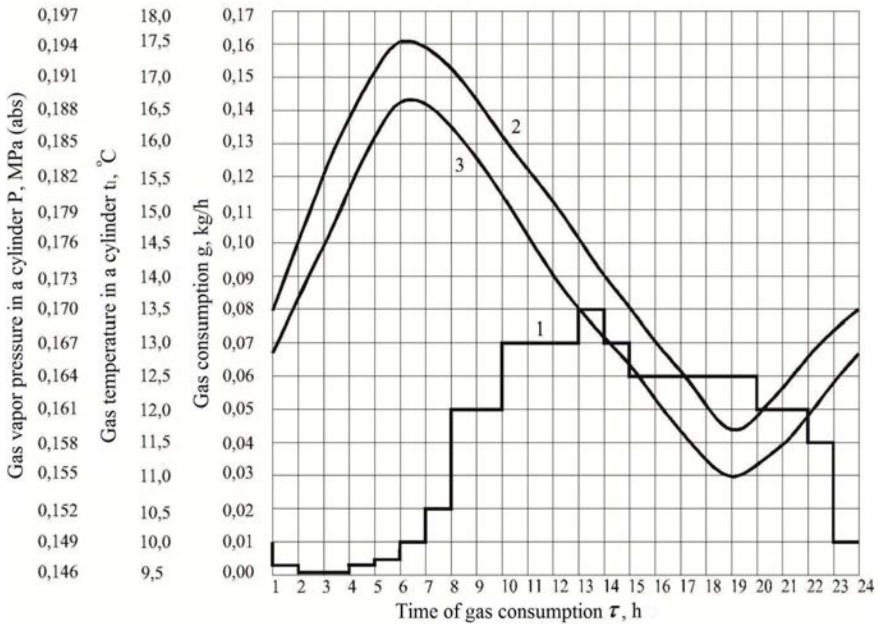

Fig. 3: Performance of a cylinder for residual filling level of 24% (gas consumer is 4-burner gas stove): 1: gas consumption g (kg/h); 2: gas temperature in a cylinder t_l, °C; 3: gas vapor pressure in a cylinder P, MPa (abs)

- Grade of liquefied hydrocarbon gas supplied: commercial propane-butane
- Minimum gas pressure in cylinder according to conditions of stable operation of pressure controller 0.14÷0.15 MPa (abs)
- Occupation density factor of the apartment 3 man/ap
- Gas equipment of the apartment: 4-burner gas stove PG-4; 4-burner gas stove PG-4 and gas water heater VPG-23
- Hourly dynamics of gas consumption for a day of maximum gas consumption (31th December) by apartments equipped with gas stoves as well as gas stoves and water heaters in percents of daily gas consumption, obtained from data of experimental observation is given in Kuritsyn (1988)
- Gas temperature in a cylinder at the beginning of operation was assumed equal to ambient air temperature t_β = 18°C

Gas temperature in the end of jth time interval $t^k_{ж, j}$ was determined by Eq. 5 for specified value of hourly gas consumption g_j and specified value of gas level in a cylinder φ_j. Then composition of liquefied gas and pressure of vapor blanket P, MPa in the end of regular vapor extraction was determined. Required value of gas residual level in a cylinder φ_{res} was obtained by the method of variants calculation in order to implement the condition P≈0.15 MPa (abs).

The study carried out has determined that residual level of liquefied gas in a cylinder in case if a consumer has 4-burner gas stove installed shall be not less than 24% in case of 4-burner gas stove and instantaneous water heater -32%. Performance of a cylinder unit is shown in curves (Fig. 3 and 4).

For operation of gas stove and residual (buffer) level of cylinder filling with liquefied gas φ_{res} = 24% (Fig. 3), minimum vapor pressure of 0.155 MPa (abs) is present in evening time (7÷8 pm) at minimum LHG temperature of 11.8°C. In the nighttime, due to rapid decrease of gas consumption, liquid phase temperature will increase and in the end of night operating period, virtually restore up to ambient temperature.

Similar pattern is observed for operation of gas stove and instantaneous water heater (Fig. 4). For residual filling level of a cylinder φ_{res} = 32%, minimum vapor pressure of 0.147 MPa (abs) is present in the nighttime (10÷12 pm) at minimum LHG temperature of 10.1°C. In the following hours, gas temperature will increase and virtually restore up to ambient temperature. Calculations have shown that residual gas level in a cylinder forms consumer's gas buffer stock that provides operation of 4-burner gas stove for 8 days and operation of 4-burner gas stove and instantaneous water heater for 7 day in case of untimely exchange of cylinders by gas service personnel.

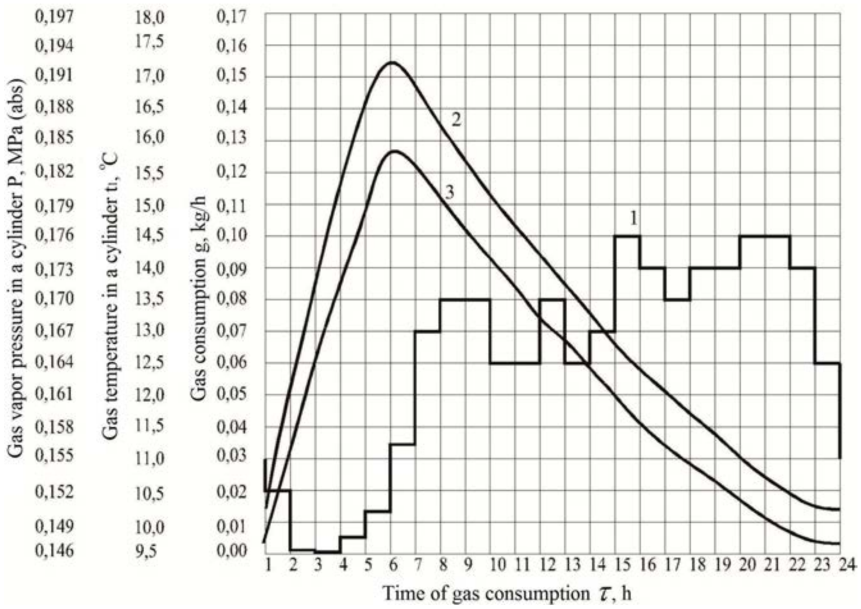

Fig. 4: Performance of a cylinder for residual filling level 32% (gas consumer is 4-burner gas stove and instantaneous water heater): 1: gas consumption g (kg h^{-1}); 2: gas temperature in a cylinder tl, °C; 3: gas vapor pressure in a cylinder P, MPa (abs)

CONCLUSION

Use of outdoor gas cylinder units is recommended for provision of gas supply to temporary (seasonally) functioning facilities at positive ambient temperatures.

Installation of cylinders with the capacity of 50 L inside the heated rooms and their operation at positive ambient air temperatures (+10°C and higher) provides operation of 4-burner gas stove with maximum provision of gas consumption for 22 days and 4-burner gas stove and instantaneous water heater for 12 days.

In order to maintain maximum provision of gas supply, residual level of liquefied gas in a cylinder in case if a consumer has 4-burner gas stove installed shall be not <24% in case of 4-burner gas stove and water heater -32%.

Calculations have shown that residual gas level in a cylinder forms consumer's gas buffer stock that provides operation of 4-burner gas stove for 8 days and operation of 4-burner gas stove and instantaneous water heater for 7 days in case of untimely exchange of cylinders by gas service personnel.

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