Centralization of gas supply systems based on butane-air mixture

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Abstract. The expansion of the construction of cottage villages, isolated settlements in ecologically clean areas, away from large cities, as well as the provision of gas to the settlements of the eastern part of the Russian Federation, sets the task of developing autonomous gas supply systems. A significant deterrent to the development of autonomous gas supply systems based on butane mixtures with air is their high cost and the absence of scientifically sound recommendations for choosing system parameters. To develop scientifically sound recommendations for the design of systems, considering all the factors of influence that ensure the optimal cost of gasification and subsequent maintenance by the consumer, additional studies are necessary. The article considers the choice of optimal centralization of gas supply systems based on a mixture of butane with air to determine the minimum cost of construction and operation for consumers. The systems analysis, mathematical model methods with calculation of optimal values in the presence of corresponding limits and the methods of material correlation processing are used. The data have been obtained for effective centralization of gas supply systems based on butane-air mixture. The criteria are set which influence the optimum number of houses connected to a tank installation, such as population density in a gas supplied area, climatic features of an area, a type of consumer’s gas-using equipment and a form of settlement development. As a result of the research, the optimum number of apartments has been determined for gas supply to a settlement connected to a tank installation. These recommendations will make it possible to increase efficiency of gas supply source selection and consumer connecting to a gas supply network at minimum cost for consumers.

1. Introduction

Nowadays, suburban settlements, farm with residential households and other housing communities are being built actively, and their remoteness from natural gas mains at the moment makes natural gas supply impossible. [1, 2, 3].

Traditionally, autonomous gas supply systems based on hydrocarbon mixtures serve as a replacement for network natural gas [4, 5]. These systems include a gas supply source, a distribution network of gas pipelines and a consumer. The significant cost of a gas supply source in the form of gas holders of various volumes determines the high cost of autonomous systems per one gasified house. This circumstance limits the widespread introduction of these systems into practice. One of the reserves for reducing the cost of gasification is centralization, that is, the enlargement of gas supply sources (tank installation volume), the design of an extensive gas distribution network and the connection of a significant number of houses to it. Thus, the number of objects connected to one tank
installation and the determination of system parameters and the main criteria for which autonomous gasification takes precedence is an urgent task.

2. Review of literature
The practice of centralized system operation showed that typically 100-150 apartments equipped with gas stoves and 50-70 apartments equipped with stoves and hot water boilers are connected to one tank installation in the natural regasification mode [6, 7]. Given the need to ensure a comfortable stay of residents and gas consumption for all household needs, such centralization does not meet modern requirements for uninterrupted gas supply, especially during maximum gas consumption in the morning and evening hours. Additional disadvantage is significant system steel intensity per one unit of evaporated and supplied to consumer gas resulting in significant initial and operation cost of a system.

In the existing literature, the scientific recommendations on issues of a LHG-based gas supply system centralization with artificial evaporation have a wide range of recommended centralization values [8, 9, 10]. Thus, for example, the optimum centralization of municipal gas supply systems for housing estates with 2-story buildings is 350-800 apartments according to [8] and 1200 - 3600 apartments according to [9, 10] providing that apartments are equipped with gas stoves, i.e. it differs by more than 4 times. To some extent, the mentioned difference can be explained by significant flatness of the objective function. Presuppositions and assumptions considered when setting the task also have significant influence on the research results. At the same time, it should be noted that the above recommendations do not take into account the possibility of using LPG for heating needs and thus do not allow the use of these recommendations in modern gas supply practices.

In accordance with the above, the justification of the optimal centralization of gas supply systems based on gas-air mixtures for gas supply to settlements, taking into account the supply of gas to consumers for all domestic needs, is an urgent scientific and technical task.

3. Materials and methods
As the target function of the specified optimization problem, let’s take the specific cost (per one gasified apartment) of a gas supply system in the following set: a group tank installation with a unit for gas-air mixture treatment and storage – distribution circuits - consumer.

\[ C_{\text{gas}}(n) + C_{\text{butane-air-pipeline}}(n) = \min, \]

Where \( n \) is a number of houses connected to one RUSUG, (h); \( C_{\text{gas}}(n) \) is a cost of tank installations and a unit for butane-air mixture treatment and storage, (\$·y\(^{-1}\)·h\(^{-1}\)); \( C_{\text{butane-air-pipeline}}(n) \) is a cost of street gas supply systems, (\$·y\(^{-1}\)·h\(^{-1}\)).

According to the technical-economical analysis, the cost of intrafacility gas supply systems (yard inputs, domestic gas pipelines and installations using gas) remains the same at any centralization of gas supply settlement systems, so they may be excluded from the target function when considering variables[1].

The cost of tank installations \( C_{\text{gas}}(n) \) depends on a capacity of consumer’s gas holders determined by the annual volume of consumed gas. Scientific studies revealing this issue are presented in publications [11, 12, 13]. An analysis of scientific publications shows that the climatic features of the area, the level of thermal protection of the building, the type of gas consuming equipment by the consumer have a significant influence on the volume of the gas supply source [13, 14, 15, 16]. The mathematical modeling in economics resulted in finding correlation dependencies to determine a required quantity of air-gas mixture for household needs of buildings depending on climatic zones of facility operation, taking into account an optimal configuration of a facility under study:

- cold climate zone

\[ G_{\text{butane-air}} = 451.42t_{\text{h}}^{0.4981}, \quad R=0.99 \]

- moderately cold climate zone
- moderately warm climate zone

\[ G_{\text{butane-air}} = 324.42 F_{\text{fl}}^{0.5076}, \quad R=0.99 \]  

\[ G_{\text{butane-air}} = 203.35 F_{\text{fl}}^{0.5114}, \quad R=0.99 \]

Where \( F_{\text{fl}} \) is an area of a building floor, (m²).

It is recommended to accept at least 2 tanks for installation for consumer gasification depending on annual consumption and the regulatory literature requirements for assuring the required gas supply conditions (Table 1).

| Parameter                      | Gas holder capacity \( V_p \), (m³) |
|-------------------------------|-------------------------------------|
| Number of gas holders in an   | 1.0       | 1.5       | 2.6       | 4.8       |
| installation                  | 2         | 2         | 2         | 2         |
| Recommended annual gas        | \( \leq 15 \) | 15-25     | 25-45     | 45-100    |
| consumption \( Q_y \), (t·y⁻¹) |                                      |           |           |           |

The cost of group tank liquefied hydrocarbon gas installations is determined according to the formula:

\[ C_{\text{gas}}(n) = n^{-1} \left( k(C_g + C_h + C_{el} + C_{bl}) + \varphi_g C_g + \varphi_h C_h + \varphi_{el} C_{el} + \varphi_{bl} C_{bl} + E_l \right) \]  

Where \( C_g \) is a cost of underground gas holders, ($) ; \( C_h \) is a cost of reducing heads, ($) ; \( C_{el} \) is a cost of an electric evaporator, ($) ; \( C_{bl} \) is a cost of a unit for air-butane mixture production and gas-air mixture storage, ($) ; \( k \) is a capital investment efficiency factor, (y⁻¹) ; \( \varphi_g \) is a share of annual allocations for operation of underground tanks, (y⁻¹) ; \( \varphi_h \) is a share of annual allocations for operation of reducing heads, (y⁻¹) ; \( \varphi_{el} \) is a share of annual allocations for operation of an electric evaporator, (y⁻¹) ; \( \varphi_{bl} \) is a share of annual allocations for operation of a unit for air-butane mixture production and gas-air mixture storage, (y⁻¹) ; \( E_l \) is an annual cost of power used for liquefied gas regasification, ($·y⁻¹)

According to the formulas (1-3) and the table 1, the calculations were performed to determine the cost of the group tank installations with electric evaporators depending on the number of gasified apartments [17]. Processing of the results allowed us to derive the analytical expression to determine the cost according to the number of gasified houses:

\[ C_{\text{gas}}(n) = 16318.5 \cdot n^{-0.62} \]  

The curvilinear correlation of the exponential function is 96.4% at 7.6% maximum deviation of estimated costs from the approximating dependence.

The cost of distributing pipelines generally depends on their length and average diameter [1, 8, 9, 10]. For the gas supply systems on the basis of commercial butane, the most dangerous is moisture condensation in gas-air mixture and hydrate formation. According to the studies [18, 19, 20], usage of gas-air mixture for gas supply to consumers ensures dew point reduction, meanwhile the ambient temperature accepted for designing in most operating climatic zones of the Russian Federation is lower than the temperature of gas-air mixture hydrate formation. Thus, the above-ground routing of low-pressure gas pipelines is not recommended at settlement gasification on the basis of commercial butane. Thus, the most optimal option for laying gas distribution networks during gas supply to consumers with mixtures of propane and, butane and air is to place gas pipelines underground below the freezing depth of the soil.

In this case, the specific cost of distributing gas pipelines is determined according to the following formula:

\[ \text{Cost} = \text{Formula} \]
\[ C_{\text{butane-air-pipeline}} n^{-1} = n^{-1}(kC_{\text{butane-air-pipeline}} + OC_{\text{butane-air-pipeline}} n^{-1}) \quad (7) \]

Where \( C_{\text{butane-air-pipeline}} \) is a cost of street gas pipelines, ($); \( OC_{\text{butane-air-pipeline}} \) is an operation cost of distributing gas pipelines, ($·y^{-1}$).

The calculations were performed to determine the cost of gas supply systems. The following initial data were used in the calculations:

- settlement development type: district or ribbon development;
- for calculation, a settlement with the following gas supply facilities was adopted - cottages with a base area of 64 (m²), 100 (m²), 256 (m²) with a full level of engineering service;
- the number of apartments in one building \( n_0 = 1 \);
- the population density in the area supplied from one tank installation \( q = 0.5 \times 10^{-3} \text{(per·m}^{-2}) \), 2.5 \times 10^{-3} \text{(per·m}^{-2}) \), 5 \times 10^{-3} \text{(per·m}^{-2}) \).

According to the calculation results, the system cost increases with the increase in number of houses connected to the tank installation regardless the operation area and the type of gas-using equipment installed by a customer.

Distribution of gas consumers over the gas supplied area influences significantly the cost of the gas supply system. For example, if the population density is 0.5 \times 10^{-3} \text{(per·m}^{-2}) \) and the number of houses gasified from one tank installation \( n = 30 \), the cost is 15500 ($·h^{-1} \text{) per one gasified house at two-lane development in the cold climatic zone area provided that building are equipped with gas stoves and batch furnaces, and the cost is 4140 ($·h^{-1} \text{) in the moderately warm zone in the same conditions provided that the population density is 0.5 \times 10^{-3} \text{(per·m}^{-2}) \), that differs by 3.7 times. This tendency can be traced at any settlement development and any gas consumption by gas-using equipment.

At the same time, the climatic zone of gas network laying has no significant influence on the cost, the divergence of cost values is 0.1-0.6%. The detailed study of the target function (7) in respect of settlement with villa development and the following processing of numeric results using a computer made it possible to derive the approximating equations to determine the gas supply system cost depending on the determining factors (Table 2).

| Service type                                                                 | Batch-operated stoves and boilers at the existing level of a building thermal protection | Stoves and boilers of continuous operation at increased level of building thermal protection | Gas stoves, hot water boilers and heating boilers of continuous operation at increased level of building thermal protection |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Two-lane development                                                         | 28671 \cdot n^{-0.7} + 203q^{-0.49}n^{0.19}                                              | 28671 \cdot n^{-0.7} + 220q^{-0.5}n^{0.142}                                              | 28671 \cdot n^{-0.7} + 210q^{-0.49}n^{0.157}                                                   |
| Multilane development                                                        | 28671 \cdot n^{-0.7} + 215q^{-0.49}n^{-0.143}                                           | 28671 \cdot n^{-0.7} + 213q^{-0.469}n^{0.136}                                            | 28671 \cdot n^{-0.7} + 219q^{-0.496}n^{0.12}                                                  |

4. Study results

Differentiation of the expressions in table 2 by the control parameter \( n \), substitution of the population density values in the gas-supplied territory made it possible to derive the optimal number of apartments gasified from one tank installation (Table 3).
Table 3. Optimum centralization of supply systems on the basis of butane-air mixture.

| Population density on the gasified area \( q, \text{ (per \( \cdot \) m}^2) \) | Centralization at the settlement development | Allowable range of gas supply system centralization at mixed settlement development |
|---|---|---|
| | Multilane | Two-lane | |
| | optimum \( n_{opt} \) | allowable | optimum \( n_{opt} \) | allowable |
| Farm buildings with the existing thermal insulation level. | | | |
| Gas equipment – batch-operated gas stoves, gas heating stoves | | | |
| 0.5 \( \cdot \) 10\(^{-3} \) | 59 | 19 - 106 | 39 | 14 - 67 | 19 - 67 |
| 2.5 \( \cdot \) 10\(^{-3} \) | 107 | 53 - 206 | 66 | 41 - 151 | 53 - 151 |
| 5 \( \cdot \) 10\(^{-3} \) | 201 | 90 - 400 | 121 | 63 - 252 | 90 - 252 |
| Farm buildings with increased thermal insulation level. | | | |
| Gas equipment – gas stoves, gas heating stoves (boilers) of continuous operation | | | |
| 0.5 \( \cdot \) 10\(^{-3} \) | 62 | 31 - 152 | 42 | 17 - 100 | 31 - 100 |
| 2.5 \( \cdot \) 10\(^{-3} \) | 146 | 77 - 385 | 102 | 44 - 212 | 77 - 212 |
| 5 \( \cdot \) 10\(^{-3} \) | 286 | 119 - 782 | 198 | 88 - 377 | 119 - 377 |
| Villas with increased thermal insulation level. | | | |
| Gas equipment – gas stoves, hot water boilers and heating boilers of continuous operation | | | |
| 0.5 \( \cdot \) 10\(^{-3} \) | 62 | 26 - 155 | 42 | 17 - 106 | 26 - 106 |
| 2.5 \( \cdot \) 10\(^{-3} \) | 148 | 74 - 389 | 99 | 50 - 228 | 74 - 228 |
| 5 \( \cdot \) 10\(^{-3} \) | 242 | 108 - 648 | 185 | 94 - 430 | 108 - 430 |

As the Table 3 shows, the range of allowed values of settlement gas supply system centralization at two diametrically opposed variants of settlement development has a wide overlap area. This makes it possible to accept the specified area as the allowable range of settlement gas supply system centralization at mixed (two- and multilane) development structure. Such type of development represents more adequately the actual development of settlements and ensures maximum adaptation of made recommendations to particular characteristics of actual designing.

5. Conclusions

Data were obtained on the optimal centralization of gas supply systems based on the butane-air gas-air mixture. We have made the following conclusions:

- it is found that several factors influence the number of houses connected to a tank installation: gas consumption rate, population density on a gas-supplied area, type of settlement development.
- the recommendations were made concerning optimum functioning of settlement centralized systems, and also the allowable centralization range was determined at mixed type of settlement development.

6. Confirmations

The results of scientific research were reported at international conferences and published in scientific articles [11, 12, 13, 18]. The studies were carried out at the Saratov State Technical Uni-versity named after Gagarin Yu.A. according to the program of state budget research “Development of modern technologies and materials to ensure energy and resource conservation, reliability and safety of objects of the architectural and construction complex”.

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