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Contemporary trends in metropolitan gas distribution infrastructure construction

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Scope of Study: Current development trends for all gas infrastructure systems utilizing natural gas and alternative fuels (most commonly, liquefied hydrocarbon gas) do not provide due justification for all criteria influencing the efficiency of such systems. Meanwhile, expediency of natural or liquefied gas supply shall be calculated by taking into account network configuration for settlements, their population density, type of gas equipment utilized by customers and other relevant factors. Very often, dismissal of such criteria leads to tremendous and unjustified investment into gas distribution systems, thus decreasing their economic viability and efficiency.
The purpose of this study is development of an optimal structure for natural and liquefied hydrocarbon gas distribution system that taken into account individual characteristics of gas fuel consumption by metropolitan community.
Materials and Methods: The study is based on generalization and systematization of gasification data provided by gas distribution companies operating in Russian Federation. System analysis and mathematical simulation have been used to find optimal values for relevant limitations.
Results: Optimal operation parameters of gas distribution system utilizing natural and liquefied hydrocarbon gas and taking into account gas consumption rates have been found. System analysis of elements of distribution system under construction allowed estimating the number and specific features of gas fuel consumption in various settlements, number of said settlements and their annual gas consumption rates and number of distribution stations in terms of regional supply of natural and liquefied hydrocarbon gas.
Conclusions: We have evaluated gas distribution systems parameters based on annual gas consumption rates. The scope of application for natural and liquefied hydrocarbon gas within specified gasified region has been established. We have also provided recommendations on practical application of obtained research data.

1. Optimal centralization of inter-settlement gas supply systems utilizing piped natural gas.

Currently, the prevalent type of piped natural gas supply systems is inter-settlement gas supply system. The base point of such inter-settlement gas supply systems is gas distribution station (GDS) which receives natural gas from the main gas pipeline branch. As the number of settlements requiring natural gas supply is significant and those settlements are scattered over a large area, preliminary technical and economical survey shall determine the most rational location for GDS. The number of settlements connected to a single GDS within inter-settlement gas supply system shall be determined on the basis of economic survey which takes into account various technical (technological), geographical, climatic and geological features of gas supply territory, location of settlements, their gas consumption, GDS output capacity and other factors.

Optimal rate of centralization for inter-settlement piped gas supply systems, M, is determined on the basis of specific cash costs for the process chain consisting of gas pipeline branch – M_{ogp}; gas distribution station – M_{gds}; and inter-settlement gas pipeline – M_{isgp}. In this case, the optimal performance of inter-settlement gas supply system can be evaluated as follows:

$$M=\left[\frac{M'_{gds}}{\left(\frac{N_{inh}}{F}\cdot\pi\cdot R^2\right)}+\frac{3R\left(2M'_{isgp}+M'_{ogp}\right)}{n_{av}}\right]=\min, \quad (1)$$

where M'_{gds} is total cash costs for pipeline construction and operation which depend on the GDS design and output capacity, ($\$\cdot y^{-1}$); R is GDS operating range, (km); n_{av} is average population of settlements, (inh); N_{inh} is total population of the agglomeration (region, administrative district), (inh); F is agglomeration area, (km^2); q is rural population density, ($inh\cdot km^{-2}$):

$$q=\frac{N_{inh}}{F}, \quad (2)$$

where M'_{isgp} is presented specific cash costs per 1 km of inter-settlement pipeline, ($\$\cdot y^{-1}\cdot km^{-1}$):

$$M'_{isgp}=a+b\cdot d, \quad (3)$$

where a,b are the coefficients specific per 1 km of inter-settlement pipeline, ($y\cdot km^{-1}$), ($y\cdot km^{-1}\cdot cm^{-1}$); d is diameter of inter-settlement pipeline, (cm):

$$d=\left[\frac{\frac{P_0}{0.5(P_{in}+P_{fin})}\cdot B\cdot\rho_0\cdot\frac{n_{av}}{S}\sum_{i=1}^{n}g_i\cdot k_{o,i}}{\frac{\Delta P_{adm}}{1{,}1L}}\right]^{1/m_1}, \quad (4)$$

where A, B, m, m^1 are the coefficients specific to the pipeline category (pressure-specific) and pipeline material as specified in [3]; ρ_0 is gas density under normal conditions, ($kg\cdot m^{-3}$) P_0 is atmospheric pressure, (MPa); P_{av} is average (absolute) gas pressure within the pipeline, (MPa):

$$P_{av}=\frac{P_{in}+P_{fin}}{2}, \quad (5)$$

where P_{in}, P_{fin} is absolute gas pressure indices at the input and output of inter-settlement gas pipeline respectively, (MPa); Q_{il}^{m} is maximal hourly gas consumption rate for a single settlement (depending on the population of such settlement), ($m^3\cdot h^{-1}$), which is calculated depending on an average number of people per apartment, type of gas equipment, its operation mode and other factors specific to gas equipment:

$$Q_{il}^{m}=\frac{n_{av}}{S}\sum_{i=1}^{n}g_i\cdot k_{0,i}; \quad (6)$$

where S is apartment population coefficient, ($per\cdot ap^{-1}$); g_i is gas consumption of *i*-th gas equipment (gas stove, gas boiler, gas heater), (($m^3\cdot h^{-1}$)); $k_{0,i}$ is coefficient of simultaneous operation of gas appliances (as specified in [3]); ΔP_{spec} is specific pressure loss for medium- and high-pressure pipelines, ($MPa\cdot m$), and specific pressure loss for low-pressure pipelines, ($Pa\cdot m$):

$$\Delta P_{spec}=\frac{\Delta P_{adm}}{1.1L}, \quad (7)$$

where ΔP_{adm} is permissible pressure loss, (MPa); L is the distance to the most remote point of gas pipeline, (m).
The diameter value calculated in the accordance with the formula (4) shall be rounded up to standard values specified as follows [2, 3]:
- the closest greater diameter for steel pipelines;
- the closest lower diameter for polyethylene pipelines.

Total number of settlements to be supplied with gas via a single GDS, *Amt*, shall be calculated as follows:

$$Amt = \frac{\pi \cdot q \cdot R^2}{n_{\text{av}}}, \tag{8}$$

Taking into consideration that each settlement requires a separate pipeline, the total length of inter-settlement pipelines shall be:

$$L_{\text{isgp}} = \frac{2\pi \cdot q \cdot R^3}{3n_{\text{av}}}. \tag{9}$$

Calculation should also account for gas consumed by any industrial enterprises located in a particular settlement as a certain ratio of gas consumption by residential areas, Q_{il}^{m}. Design output capacity of GDS is determined by total gas consumption of all settlements connected to the station:

$$Q_{\text{gds}} = Q_{\text{il}}^{\text{m}} \cdot Amt. \tag{10}$$

This equation system (1÷11) forms economical and mathematical basis of the task. Based on the analysis the initial performance function depends on the station range of operation $M = f(R) = \min$. Its minimal value can be determined by variants calculation. Costs of gas supply system $M_1, M_2, ..., M_{\text{i}}, ..., M_{\text{n}}$ can be calculated by setting several values of the station operation range $R_1, R_2, ..., R_{\text{i}}, ..., R_{\text{n}}$. Minimal cost value, $M_{\min}$, corresponds to the optimal value of the control parameter R_{opt}.

Optimal range of a station operation, R_{opt}, with a preset value of inter-settlement gas pipeline diameter $d = \text{const}$ ($M_{\text{isgp}}^{/} = \text{const}$) shall be determined as follows:

$$R_{\text{opt}} = \left(\frac{3M_{\text{gds}}^{/} \cdot n_{\text{av}}}{M_{\text{isgp}}^{/} \cdot q \cdot \pi} \right)^{1/3}. \tag{11}$$

In such a case optimal number of settlements to be connected to a single GDS, Amt_{opt}, is calculated based on the pre-established optimal operation range of such GDS:

$$Amt_{\text{opt}} = \frac{\pi \cdot q \cdot R_{\text{opt}}^2}{n_{\text{av}}}. \tag{12}$$

Optimal location for GDS construction shall be chosen on the basis of the following guidelines.

The problem can be defined as follows: gas distribution station supplies m settlements located within certain region (administrative area) at points marked with coordinates $x_1, y_2, ..., x_2, y_2, ..., x_{\text{i}}, y_{\text{i}}, ..., x_{\text{m}}, y_{\text{m}}$, with natural gas. Maximal hourly rate of gas consumption by settlements is $Q_{\text{il, 1}}^{\text{m}}, Q_{\text{il, 2}}^{\text{m}}, ..., Q_{\text{il, i}}^{\text{m}}, ..., Q_{\text{il, m}}^{\text{m}}$. We have to fix coordinates for the gas distribution station location. At the same time, its location may be constrained by geographic factors such as rivers, lakes, hills etc.

The total cash costs for construction and operation of inter-settlement gas pipelines, M_{isgp}, shall be taken into consideration as criterion for solving our problem.

The optimal solution to the problem is based on the following:

$$M_{\text{isgp}} = \sum_{\text{i}=1}^{\text{m}} M_{\text{isgp,i}} = \min, \tag{13}$$

where $M_{\text{isgp,i}}$ is fixed cash costs for construction and operation of *i-th* inter-settlement pipeline, $\$ \cdot y^{-1}$.

Differentiation of the target function (13) by control parameters *x* and *y* produces a set of equation; solution of such set of equations produces the optimal values of control parameters (GDS location coordinates) $x_{opt}; y_{opt}$. Gradient projection method is used to determine the optimal location for gas distribution station. The defined problem is solved via software application that accounts for settlement and pipeline system design features (Certificate on Official Registration of the Computer Program No. 2009616985).

2. Optimal centralization of inter-settlement gas supply systems utilizing the liquefied petroleum gas.

While gas supply system utilizing piped gas has many advantage, it should be noted that commercial viability of such gas supply system is restricted by a customer distance from major pipelines and a settlement size. Based on our studies, maximal viable distance between a settlement with a population of 300 or less and a major gas pipeline makes 11 km [4]. At increasing the distance between such a settlement and major pipeline, and decreasing a settlement population, subject to the absence of any consistent gas consumers (industrial objects), the liquefied petroleum gas (LPG) becomes more commercially viable for supplying such a settlement.

LPG application is also viable for constructing gas supply system within territories with uneven gas consumption profiles caused by significant decentralization of customers whose annual gas consumption ranges from 5 tons per year (individual housings) to 100 tons per year (farming and industrial enterprises).

In this case, gas supply system shall be formed on the basis of gas filling station (GFS) with required quantity of gas fuel supplied to customers utilizing LPG cylinders or gas storage tanks; such gas supply system is called a mixed-type system [5, 6, 7].

Specific fixed cash costs for LPG-based mixed-type gas supply system are calculated as follows:

$$M = \frac{1}{\pi^{0.8} q_{gfs}^{\;0.8} R_{gfs}^{1.6}} \left\{ A_t p^{0.2} + A_c [1 - p]^{0.2} + [0.8 b_t R_{gfs} + M_{ot}] p + [0.8 b_c R_{gfs} + M_{oc}][1 - p] \right\}, \quad (14)$$

where A_t, A_c, are cost parameters dependent on gas selling procedures, ($\$\cdot t^{-1}$); p is the percent of customer utilizing LPG storage tanks; R_{gfs} is GFS range of operation, (km); q_{gfs} is gas customer density within the area adjacent to GFS, ($t\cdot y^{-1}\cdot km^{-2}$); M_{ot}, M_{oc} are cash costs including costs for gas storage tanks, gas distribution pipelines, domestic gas installations, and customer gas cylinders as well as gas transportation expenses related to method of transportation and road surface type, ($\$\cdot t^{-1}$); b_t, b_c are coefficients specific for road surface type (transportation routes).

Costs for LPG storage tanks and distribution pipelines shall correspond to the optimal design parameters for gas distribution system as detailed in [8] and generally defined as the following functional relationships:

- for gas storage tanks:

$$M_t(n) = \frac{1}{n} \left\{ [E + \varphi_t] f\left(F_{opt}, V_t^{opt}(g_y, n)\right) + [E + \varphi_v] \psi(g_h, n) + \zeta(g_y, n, \xi) \right\}, \quad (15)$$

where E is capital investments efficiency ratio, (y^{-1}); φ_t, φ_v are the percentage of annual costs for operation of underground gas tanks and vaporizers, (y^{-1}); F_{opt} is the optimal form factor of gas storage tanks; V_t^{opt} is the optimal gas storage tank volume, (m^3); g_h, g_y are maximal hourly ($kg\cdot h^{-1}\cdot ap^{-1}$) and annual ($kg\cdot y^{-1}\cdot ap^{-1}$) gas consumption rates per a single apartment; ξ is the coefficient specifying natural evaporation capacity of underground gas storage tanks within general balance of evaporation capacity.

- for settlement gas distribution systems:

$$M_{gs}(n) = \frac{1}{n} \{\{\{[E + \varphi] f \{\{d\{\Delta P, G_h[g_h, n], L[l(q,S), n]\}, L[l(q,S,n)]\}\} + \mu L[l(q,S), n]\}\}\}, \quad (16)$$

where φ is the percentage of annual costs of pipeline depreciation and maintenance, (y^{-1}); d is the average diameter of distribution gas pipelines within the settlement, (m); ΔP is the pressure differential for outdoor distribution pipelines, (Pa); G_h is maximal hourly gas consumption rate for a group instal-

lation of LPG storage tanks, ($kg \cdot h^{-1}$); l is the pipe range per a single apartment with gas supply, ($m \cdot ap^{-1}$); q is the population density of gas supplied area, ($per \cdot ha^{-1}$); S is the apartment population coefficient, ($per \cdot ap^{-1}$); μ is the cost of annual maintenance of gas pipelines, ($\$ \cdot y^{-1} \cdot m^{-1}$); L is the total range of gas pipelines per one group installation of gas storage tanks, (m).
Specific parameters contributing to gas transportation expenses and specific for transportation and road surface type are covered in [9].
Equation (14) characterizes the $0<p<1$ constraint that provides flexibility in practical application of gas supply systems. The reasons for gas cylinder or storage tank application are based on the customer satisfaction with public utility services which is directly connected to annual gas fuel consumption rate and sufficiency of provided gas supply [8, 10]
If case there is no any mixed-type gas supply system located within the gas supply area, equation (14) is transformed into following equations:
- if gas customers utilize cylinder units for gas supply (p=0)

$$M = \frac{A_c}{\pi^{0.8} q_{gfs}{}^{0.8} R_{gfs}^{1.6}} + 0.8 b_c R_{gfs} + M_{oc}; \qquad (17)$$

- if gas customers utilize gas storage tanks for gas supply (p=1)

$$M = \frac{A_t}{\pi^{0.8} q_{gfs}{}^{0.8} R_{gfs}^{1.6}} + 0.8 b_t R_{gfs} + M_{ot}; \qquad (18)$$

Using a variable-based approach to solve equation (14) allows us to determine the optimal GFS range of operation R_{gfs}^{opt}, km, in such a case, required parameters can be calculated as follows:
- for mixed-type LPG supply system (if $0<p<1$)

$$R_{gfs}^{opt} = \left\{ \frac{2\left[A_t p^{0.2} + A_c (1-p)^{0.2}\right]}{\pi^{0.8} q_{gfs}{}^{0.8} \left[b_t p + b_c (1-p)^{0.2}\right]} \right\}^{0.385}; \qquad (19)$$

- for LPG supply system based on gas storage tank units (p=1)

$$R_{gfs}^{opt} = \left\{ \frac{2A_t}{\pi^{0.8} q_{gfs}{}^{0.8} b_t} \right\}^{0.385}; \qquad (20)$$

- for LPG supply system based on gas cylinder units (p=0)

$$R_{gfs}^{opt} = \left\{ \frac{2A_c}{\pi^{0.8} q_{gfs}{}^{0.8} b_c} \right\}^{0.385}. \qquad (21)$$

In case we take into account the range of customer gas supply, then annual gas sales for GFS are calculated as follows:

$$N_{gfs}^{opt} = \pi q_{gfs} (R_{gfs}^{opt})^2. \qquad (22)$$

Numerical implementation of equations (14-22) allows us to find GFS parameters relative to gas customer density for gas supplied area R_{gfs}^{opt} and N_{gfs}^{opt}, these parameters are provided in Table 1.

Table 1. Parameters of a Gas filling station of LPG.

Density of gas supplied area from gas filling station q_{gfs}, ($t \cdot y^{-1} \cdot km^{-2}$)	GFS range of operation R_{gfs}^{opt}, (km)	Annual gas sales for GFS N_{gfs}^{opt}, ($t \cdot y^{-1}$)
0.2	110	35000
0.5	143	52000

1.0	175	67000
2.0	215	86000
3.0	245	104000
4.0	262	115000

Our study findings evidence that operation of gas supply system based on GFS unit can be deemed effective relative to gas customer density for a gas supplied area if the gas sales range from 35000 to 120000 tons per year with range of operation being from 110 to 262 km**.** Significant gas consumption and variable operation range of GFS is indicative of a single GFS covering a vast territory and providing gas to many settlements; therefore, we have to consider the possibility for even distribution of gas supply through several routes within a specific area by using a map referencing.

Station map referencing was performed by minimizing total LPG transportation costs for customers located in *k* settlements with allowances made for their annual consumption:

$$M_{\mathrm{d}} = \sum_{\mathrm{i}=1}^{\mathrm{k}} M_{\mathrm{di}}(a_{\mathrm{c}}; a_{\mathrm{t}}; b_{\mathrm{c}}; b_{\mathrm{t}}; l_{\mathrm{i}}; Q_{\mathrm{i}}) = \min, \quad (23)$$

where M_{di} is specific cash cost of gas supply from GFS to *i*-th settlement out of *k* settlements within gas supply area, ($\$\cdot t^{-1}\cdot km^{-1}$); Q_{i} is annual gas consumption by *i*-th settlement out of *k* settlements within gas supply area, ($t\cdot y^{-1}$); a_{t}, a_{c}, are coefficients specific for type of gas transfer to customer (gas cylinder carrier or fuel trucks); l_i is gas supply route length, (km).

Minimization of equation (23) was performed by using a least squares method implemented by a software application designed via C++Builder 8.0 programming package (Certificate on Official Registration of the Computer Program No. 2009612726).

As a result of such minimization, we have found the required coordinates for GFS location within the gas supply area. As GFS requires a well-developed infrastructure including railroads and continuous power supply sources, the station shall be placed within a settlement closest to the calculated coordinates.

3. Results

Optimal operation parameters of gas distribution system utilizing natural and liquefied hydrocarbon gas and taking into account gas consumption rates have been found. System analysis of elements of distribution system under construction allowed estimating the number and specific features of gas fuel consumption in various settlements, number of said settlements and their annual gas consumption rates and number of distribution stations in terms of regional supply of natural and liquefied hydrocarbon gas.

4. Conclusions

We have evaluated gas distribution systems parameters based on annual gas consumption rates. The scope of application for natural and liquefied hydrocarbon gas within specified gasified region has been established. We have also provided recommendations on practical application of obtained research data.

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