Mathematical Modeling of the Annual Consumption of Gas-Air Mixture on the Basis of Technical Butane for Household Needs of Individual Residential Buildings

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Abstract. Increasing share of private house building in the suburban zone of large cities, neighborhoods with townhouses, and suburban settlements with permanent residence of people requires intensive construction of engineering systems, including gas supply systems. The speed of providing built-up areas with pipeline network gas does not always keep up with the pace of housing construction, it is not economically feasible and may not be possible due to the relief features of the terrain. In this case, one of the possible sources of gas supply is autonomous gas supply systems based on gas-air mixtures. The most economically attractive one is the mixture of butane and air. At the same time, the recommendations for the determination of gas consumption regimes based on gas-air mixtures are very limited in the literature. Development of reasonable recommendations for determination of gas and air mixture consumption will ensure correct selection of gas supply elements, which causes reduction of cost of autonomous gas supply systems in general and will increase their attractiveness to the consumer.

A mathematical model for determination of annual consumption of gas-air mixture on the basis of technical butane for municipal and household needs is proposed, taking into account climatic features of the terrain, the aspect ratio of the object under study, the degree of glazing of the building facades, and the height of the floor. On the basis of the correlation analysis of mathematical modeling results, the dependences for determination of consumption of gas-air mixture for municipal and household needs of the building are proposed.

1. Introduction

At present, the share of private house building in the suburban zone of large cities has increased significantly, residential areas with townhouses and mansions are increasing. At the same time, the speed of provision of such built-up areas with natural pipeline gas does not always keep pace with the housing construction, it is not always economically feasible and possible due to the relief features of the terrain [1-3].

In this case, one of the possible sources of gas supply is systems based on liquefied hydrocarbon gases, as well as gas-air mixtures [4-13]. Gas-air mixtures are a mixture of butane or propane vapors
with air. The most economically attractive one is the mixture of butane with air. At the same time, recommendations for the determination of gas consumption regimes based on gas-air mixtures in the known literature are very limited [5, 9, 10].

To develop recommendations for determining the consumption of gas and air mixture for municipal needs, it is necessary to conduct scientific research.

In general, the consumption of gas-air mixture by the gas-based equipment of the consumer is determined by the expression:

$$G_b = G_{b-a}^{fp} + G_{b-a}^h,$$  \(1\)

where \(G_{b-a}^{fp}\) is a gas-air mixture consumption by a gas stove required for food preparation, (kgs per year); \(G_{b-a}^h\) is a consumption of gas-air heating boiler required for heating and hot water, (kgs per year). The amount of gas and air mixture consumption of the gas stove is determined by the type of gas burner installed in the gas appliance and is constant throughout the year.

In the most general terms, consumption of gas-air mixture for heating needs is determined by the formula, (kgs per year):

$$G_{b-a}^h = \frac{3.6 (Q_{bc} + Q_{inf}) (t_{int} - t_{ht}) \tau_{ht}}{Q_l^h \eta_k (t_{int} - t_{ext})},$$  \(2\)

where \(Q_{bc}\) is a heat loss through building envelope, (kJ per h); \(Q_{inf}\) is a heat loss in heating infiltrated air, (kJ per h); \(Q_l^h\) is a low heat of gas-air mixture combustion, (kJ per kg); \(\eta_k\) is a boiler efficiency; \(\tau_{ht}\) is a duration of the heating period, (hrs per year); \(t_{ht}\) is an average temperature for the heating period, (°C).

Numerous studies show that heat loss through enclosing structures depends on numerous factors: climatic features of the terrain, the level of heat protection of enclosing structures, micro-climate parameters inside buildings, building configuration [14-19]. The most common scientific works on determining the level of thermal protection of buildings on the basis of the choice of structural materials with optimization of their thickness [17-19]. As the best configuration, it is recommended to take a cubic shape of a building [15-16]. At the same time, the building is considered from the point of view of minimizing the total surface area, without taking into account the heterogeneity of the fence due to the presence of window fillings, while increase of the side of the cube definitely leads to an increase in all sides, which means that when the model is put into real practice, it will lead to an unreasonable increase in the height of the room. Recommendations for the determination of heat loss of buildings also do not contain recommendations on additional consideration of heat loss on heating of infiltrated air, which leads to their understatement and subsequently to incorrect calculations to determine the total heat loss. Thus, the existing mathematical models to determine the optimal configuration of the building need substantial analysis on the basic control parameters.

2. Theoretical formulation of the problem
Optimal configuration of the building determines the minimum heat loss of the building through enclosing structures

$$Q_b = f\{Q_{bc}(Q_a;Q_d;Q_e)\} = \min,$$  \(3\)

For the development of a mathematical model of an optimally configured building, we accept the following assumptions and limitations:

- aspect ratio of configurable building \(1 < ab^{-1} < 1 \cdot 10^{-1}\);  \(4\)
- glazing coefficient of the facade of a residential building [14] \( \rho \geq 18\% \);  
(5)  
- degree-heating period [14] \( 2000 \leq \text{DDHP} \leq 12000 \);  
(6)  
- occupancy rate of a residential building [20] \( S = 4 \text{people} \cdot \text{build}^{-1} \);  
(7)  
- room height of a residential building [21] \( h \geq 2.5 \text{m} \).  
(8)  

Show the area of enclosing structures, respectively, through the length (a), width (b) and height of the floor (h).

\[
F_{w1}, F_{w2} = ah, F_{w3}, F_{w4} = ah, F_{fl} = F_c = ab  
\]  
(9)

The exterior wall of the residential building is a heterogeneous structure due to the presence of window fillings. If you take a share of the glazing of a residential building facade as \( \rho \), then the reduced resistance of the wall is expressed by the following dependency

\[
R_{w_{\text{rel}}} = f(\rho; R_w, R_{w_{\text{win}}})  
\]  
(10)

where \( R_w \) is a heat transfer resistance of the building wall, \( (\text{Wt} \cdot \text{m}^{-2} \cdot \text{K}) \); \( R_{w_{\text{win}}} \) is a heat transfer resistance of window filling, \( (\text{Wt} \cdot \text{m}^{-2} \cdot \text{K}) \).

Taking into account (9) and (10) heat loss through enclosing structures, it is determined by the expression

\[
Q_{be} = \frac{2h(a+b)(R_w^w + R_{w_{\text{win}}}^w)}{(1-\rho)R_w^w + \rho R_{w_{\text{win}}}^w} + ab\left[R_{fl}^{-1} + R_c^{-1}\right] \left[t_{in} - t_{ext}\right]  
\]  
(11)

At the same time, when determining the consumption of gas and air mixture for heating of buildings, it is necessary to take into account the additional heat consumption for heating of infiltrated air, the volume of which varies widely from 0.2 \((\text{m}^{-3} \cdot \text{year}^{-1})\) per 1 m\(^3\) of the volume of the unused room to 30 \((\text{m}^{-3} \cdot \text{person}^{-1} \cdot \text{year}^{-1})\) per person to provide standard ventilation supply [20] Consider the most adverse option with the highest heat cost for heating the infiltration air according to the standard air supply to the rooms per one person.

Subject to the assumption in the task (7), the air exchange of the accommodation is defined as:

\[
Q_{\text{inf}} = 8.34Sc\rho[t_{\text{inf}} - t_{\text{ext}}]  
\]  
(12)

where \( S \) is an occupancy rate of a residential building, \( (\text{people per build}^{-1}) \); \( c \) is an air heat capacity \( (\text{kJ} \cdot \text{m}^{-3} \cdot \text{K}^{-1}) \); \( \rho \) is an air density, \( (\text{kg} \cdot \text{m}^{-3}) \).

Expressions (3-12) form a mathematical model to determine the minimum heat loss of an optimal configuration building.

3. Practical part

In order to implement the mathematical model (3-12), appropriate calculations were carried out. For calculations, the initial data are taken:

1. As objects of development, the following are accepted: residential buildings with areas \( F = 64\text{m}^2; F = 256\text{m}^2 \) and a different ratio of the sides \( a \) and \( b \) according to the assumption (4) in the present task.
2. The influence of climatic conditions was taken into account by variations in calculations of climatic zones of the buildings’ operation: moderately warm (Krasnodar), moderately cold (Saratov) and cold zone (Krasnoyarsk) [22, 23].
3. Resistance to heat transfer of enclosing structures according to [14].
4. Glazing of facades of the buildings under study \( \rho = 18\%, \rho = 25\% \).
5. Height of the floor of the building $h = 2.5m$, $h = 4m$.

The results of the corresponding calculations are presented in graphs (Figure 1-2).

**Figure 1.** Heat loss of a building with an area of 64 m$^2$.

**Figure 2.** Heat loss of a building with an area of 256 m$^2$. 
Analysis of the results obtained (Figures 1-2) shows that the change in the ratio of sides determining the base of the building from a square to a rectangle with the increase in the difference between the sides leads to an increase in the heat loss regardless of the climatic zone of the object construction.

The smallest loss through the fence is provided by the building in the form of a rectangular parallelepiped with a square base and the minimum height allowed for construction, regardless of the area of its square base. Reducing the configuration of the building to a square base allows providing a reduction of heat losses by 14.5-15.5%, regardless of the area of the base. The increase in glazing leads to an increase in heat losses in buildings of the same configuration of about 5%. Increasing the height of the building floor leads to an increase in the total heat loss of the building from 24 to 29% per meter of the height of the building. Increase in heat loss of a building with a square base with a ratio of sides 1/1, floor height of 2.5 m and a proportion of glazed facades 0.18 in relation to a building with an aspect ratio of 1/4, floor height of 4 m and the proportion of glazed facades 0.25, is 1.84 times provided that they are located in one and the same climate zone. Thus, it is possible to reduce the heat loss of a residential building by constructing it in the form of a rectangular parallelepiped with a square base and minimum height and share of glazing of facades.

The results of the calculation of the annual gas and air mixture consumption according to formulas (1) and (2) are presented in Table 1.

Table 1. Calculation of the consumption of gas-air mixture of individual residential buildings.

| Climate zone operation | Maximum hourly gas-air consumption for heating, (kgs per-hrs⁻¹) | Annual gas-air mixture consumption, (kgs per-year⁻¹) |
|------------------------|---------------------------------------------------------------|------------------------------------------------------|
|                        | 64m² | 256m² | 64m² | 256m² |
| moderately warm        | 0.168 | 0.82  | 1.80 | 3484.1 |
| moderately cold        | 0.168 | 1.04  | 2.20 | 5438.6 |
| cold                   | 0.168 | 1.28  | 2.64 | 7179.1 |

Analysis of table 1 shows that the climatic zone of operation and the area of the heated building significantly influence the energy consumption of the building. Processing of research results by interpolation method allowed obtaining correlation dependences for determination of the necessary quantity of gas-air mixture for municipal and household needs of buildings with sizes different from those presented in the calculations, depending on the climatic zones of operation of the object:

- cold climate zone operation \( G_b = 451.42F_{fl}^{0.4081} \), \( R=0.99 \)
- moderately cold climate zone operation \( G_b = 324.42F_{fl}^{0.5076} \), \( R=0.99 \)
- moderately warm climate zone operation \( G_b = 203.35F_{fl}^{0.5114} \), \( R=0.99 \)

4. The conclusion

Consumption of gas and air mixture for domestic needs is more determined by the load on heating. The minimum consumption of gas-air mixture identifies the optimal configuration of the individual residential building. A mathematical model of optimization of a residential building configuration is proposed, allowing to reduce heat losses through enclosing structures by bringing the configuration of the building to a square base on 14.5 -15.5%.

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