Analysis of the impact of the volume and planning parameters of a residential building on the estimated capacity of the heating system

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Abstract. This paper considers the method of assessing the impact of volume-planning solutions of a residential building on the thermal power of the heating system. The method is based on the study of the model of the estimated power of the heating system (taking into account the thermal power of the vent air heating), which represents a system of dependencies, including both the size of the building (heated volume), so the thermal characteristics of the external fencing structures (regulatory resistance of heat transmission), in the form of universal functional dependence on the basic parameters of the outer climate (estimated temperature for the design of the heating period) for the region. The results of the analysis of changes in the estimated power of the heating system from the characteristics of the building: the ratio of the size of the sides of the building in the plan, the height (floor) of the building, the area of glazing vertical fences are presented.

Energy savings in the operation of construction sites usually lies in finding a way to reduce the heat consumption of the most energy-intensive system in the building - heating. For specific climatic conditions, heating heat costs are determined by the estimated thermal power of the system, determined by the finished architectural and construction project. This approach, without first analyzing the possible consequences of a decision on the volume and planning parameters of the building, does not guarantee optimal energy consumption. However, the choice of a rational version of the building at the given basic characteristics (for example - volume) according to traditional methods is quite labor- and the conclusions are not always obvious and justified. Therefore, it seems useful to develop a simple model linking the basic parameters of the building with the estimated power of the heating system.

The estimated heat consumption of the residential building heating system is mainly determined by its heat loss, which depends on the estimated parameters of the external and internal air, the volume-planning solution of the building, the area of glazing, orientation, thermal characteristics of the fencing structures and the need to heat the ventilation air [1-4]. The large number of parameters that affect this function and the even greater variety of options in the volume-planning solutions and absolute size of buildings creates a difficulty in finding rational solutions that help to minimize heat consumption. In this work, the method of analytical expression of the parameter, characterizing the estimated heating capacity from the volume-planning and thermal characteristics of the building, was carried out. The methods of assessing and improving the efficiency of energy-saving buildings are mainly reduced to the analysis of the impact of thermal characteristics of fencing on transmission heat loss and local costs for
their implementation of the [5-8] or optimization of individual structures and systems in specific, and usually existing facilities [9-11].

As the analysis of publications shows, there is a gap in the comprehensive consideration of reducing the heat consumption of the building on the basis of the relationship of architectural, construction, thermal and economic indicators. The absence of a simple and understandable internal structure and a fairly universal model of objective characteristics, determining the optimal value of parameters that lay the foundation and building and its energy efficiency does not encourage architects and designers to work on this issue.

The purpose of this work is to develop a mathematical model of the parameter, which characterizes the estimated power of heating through the volume-planning and thermal characteristics of the building, as well as conducting an analysis showing the impact of volume-planning solutions on the level of possible heat consumption.

In this work, the estimated thermal power of the residential building heating system is accepted as the sum of transmission heat loss $Q_{tr}$, caused by the heat transfer process, and the cost of heat to heat the air $Q_v$:

$$Q_0 = Q_{tr} + Q_v$$  \hspace{1cm} (1)

Objective characteristic of the thermal efficiency of the building is the specific value of heat loss $q_o$, related to the heated volume $V$ and the difference between estimated domestic temperatures $t_a$ and outdoor $t_{H,o}$ air $[3]$:

$$q_o = \frac{Q_o}{V*(t_a-t_{H,o})} = \frac{Q_{tr} + Q_v}{V*(t_a-t_{H,o})} = q_{tr} + q_v$$  \hspace{1cm} (2)

where is $q_{tr}$ and $q_v$ - specific thermal characteristic of the building, respectively transmission and ventilation, W/m$^3$ °C.

Transmission thermal characteristic is determined from the condition $[2]$:

$$q_{tr} = \frac{P}{S} \left[ K_{cm} + \frac{A_n}{A_{cm}}*(K_o - K_{cm}) \right] + \frac{1}{H} * (0,9K_{nn} + 0,6K_{ns})$$  \hspace{1cm} (3)

where is - $S$, $P$, $H$ - respectively, the area (m$^2$) and the perimeter (m) of the base of the building and the height of the heated volume, m; $K_{cm}$, $K_o$, $K_{nn}$ and $K_{ns}$ - the ratio of heat transmission respectively to the wall, glazing, floor and ceiling, W/m$^2$ °C; $A_o$, and $A_{cm}$ - area, respectively, glazing and vertical surfaces of the building, m$^2$.

For a building that has the form of a parallelepiped with a heated volume $V$ and the attitude of the founding parties $b/a = n_b$. Let's present geometric dimensions as follows:

$$P = 2a(n_b + 1); \quad S = n_b a^2; \quad \frac{H}{a} = n_h; \quad V = a^3 n_b n_h; \quad \frac{1}{H} = \frac{(n_p n_b)^{\frac{1}{3}}}{n_b V^{\frac{1}{3}}}$$  \hspace{1cm} (4)

The heat transfer ratios of fencing structures will be expressed through the wall heat transfer factor: $\overline{K}_o = K_o / K_{cm}$; $\overline{K}_{nn} = K_{nn} / K_{cm}$; and the glazing area through the building's glazing factor $\overline{A}_o = A_o / A_{cm}$. Then the expression (3) is converted to the sight:

$$q_{tr} = \frac{K_{cm}}{V^{0.5}} * \left\{ 2 * (1 + n_b) \cdot (n_{sm} \cdot h_{sm})^{0.5} \cdot n_b^{-0.5} \cdot \left[ 1 + \overline{A}_o \cdot (\overline{K}_o - 1) \right] + (0,9\overline{K}_{nn} + 0,6\overline{K}_{ns}) \cdot (n_{sm} \cdot h_{sm})^{-1} \cdot V^{0.5} \right\}$$  \hspace{1cm} (5)

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The ventilation component of the thermal power of the heating system is determined by the amount of air $L_v$ (m$^3$/sec.) coming by infiltration into the premises of the building and the difference between the estimated internal temperatures $t_u$ and outdoor $t_{H,o}$ air:

$$Q_v = L_v \cdot c_v \cdot \rho_v \cdot (t_u - t_{H,o})$$

(6)

where $\rho_v$ and $c_v$ - respectively, the density (kg/m$^3$) and heat intensity (J/kg °C) of air.

Taking into account that modern glazing binding designs allow to regulate the breathability of translucent skylights, the air exchange of the building will be determined from the regulatory framework $L_v$. In accordance with sanitary standards, the living room should receive 3 m$^3$/hour of outdoor air per 1m$^3$ of its area. Then the expression (5) can be presented in the form of:

$$Q_v = L_v \cdot \Delta_{x,o} \cdot c_v \cdot \rho_v \cdot (t_u - t_{H,o}) = L_v \cdot S \cdot k_{sc} \cdot n_{sm} \cdot c_v \cdot \rho_v \cdot (t_u - t_{H,o})$$

(7)

where $k_{sc}$ - the share occupied by living quarters in the area of one floor; $n_{sm}$ - number of floors in the building.

The height of the heated volume of the building will represent the multiple height of one floor $h_{sm}$.

Then we have:

$$Q_v = L_v \cdot S \cdot k_{sc} \cdot n_{sm} \cdot c_v \cdot \rho_v \cdot (t_u - t_{H,o}) = L_v \cdot S \cdot k_{sc} \cdot \frac{H}{h_{sm}} \cdot c_v \cdot \rho_v \cdot (t_u - t_{H,o})$$

(8)

$$= L_v \cdot \frac{k_{sc}}{h_{sm}} \cdot V \cdot c_v \cdot \rho_v \cdot (t_u - t_{H,o})$$

Given that the air density in the temperature range from -20 degrees Celsius to -35 degrees Celsius varies by no more than 3% of density $\rho_{-30}$ = 1.42 kg / m$^3$, equation for the ventilation component $q_v$ specific thermal characteristics can be rewritten as:

$$q_v = 1.19 \cdot \frac{k_{sc}}{h_{sm}}$$

(9)

Given the considerations, we will finally receive:

$$q_v = \frac{K_{cm}}{V^{0.5}} \cdot \left\{ \frac{2 \cdot (1 + n_p) \cdot (n_{sm} \cdot h_{sm})^{0.5} \cdot n_{b}^{-0.5} \cdot [1 + \bar{\rho} \cdot \left( K_n - 1 \right)]}{(0.9 K_{sm} + 0.6 K_{ns}) \cdot (n_{sm} \cdot h_{sm})^{-1} \cdot V^{0.5}} + 1.19 \cdot k_{sc} \cdot h_{sm}^{-1} \right\}$$

(10)

Thus the resulting expression (9) fully reflects all the characteristics of the building and can be used to solve the problem.

To analyze the effect on the separate heating characteristic $q_o$, the building's volume-planning parameters will set the values of the thermal transmission ratios of fencing structures at the regulated level [12,13]. For the exterior walls $K_{cm}$ it is recommended to determine by the expression:

$$K_{cm} = 1/(0.00035 \cdot T_{rt} + 1.4)$$

(11)

where is $T_{rt}$ - Grad-Tag-Heizzeit:

$$T_{rt} = (t_u - t_{or}) \cdot \tau_{or}$$

(12)

where is $t_{or}$ - and translucent fences °C; $\tau_{or}$ - estimated duration of the heating period, day.

Relative heating ratios over the basement $\bar{K}_{ns}$, attic overlap $\bar{K}_{nm}$ and translucent fences $\bar{K}_{o}$ accordingly, they will determine how:

$$\bar{K}_{ns} = (0.016 \cdot \ln T_o + 0.541) / \bar{K}_{nm} = (0.0096 \cdot \ln T_o + 0.681)$$

(13)
\[
\bar{K}_o = 10^{-6} \cdot (0.0123 \cdot T_{ir}^2 + 241.6 \cdot T_{ir}) + 2.42
\] (14)

Distribution analysis from the calculated temperature of outdoor air for heating \( T_{H,o} \) for the human settlements that characterize the main climatic zones of the country [14,15] (figure 1) shows a certain dependence between them.

![Figure 1](image)

**Figure 1.** Distribution of the degree-day heating period from the estimated temperature of outdoor air for heating.

![Figure 2](image)

**Figure 2.** Change in the specific heating characteristics of the building from the floors at a) and b).

Taking the characteristic temperature of the internal air for residential buildings at 20 degrees Celsius, respectively, we will get an expression for the main argument \( T_{ir} \), determine the amount of heat transfer ratios from the calculated climate characteristic - \( T_{H,o} \) :

\[
T_{ir} = 2248 - 32 \cdot T_{H,o} + 2253 \cdot T_{H,o}^2
\] (15)
The results of the assessment of the impact of the building's volume-planning solution on the specific power of the heating system, based on equations (9, 10, 12, 15) are shown in the graphs (figure 2-5).

For high-rise buildings there is a certain minimum of specific heating capacity. Almost regardless of the volume of the building with the transition from one-story to taller buildings there is first a decrease and then an increase. At the same time, as the volume increases, this minimum shifts upwards in height and starting with a certain volume, high-rise buildings are more efficient even than single-storey buildings (figure 2 for 5,000 m³). And for "extended buildings, this trend is manifested already from two-storey objects, regardless of the estimated temperature of the outdoor air.

![Graph 3](image3.png)

**Figure 3.** Changing the specific heating characteristics of the building from the relationship of the building's sides in terms of \( n_b \) when \( t_{H,o} = -25^\circ C \) - a) and \( t_{H,o} = -35^\circ C \) - b).

![Graph 4](image4.png)

**Figure 4.** Change in the building’s specific heating characteristics from the relative glazing area \( \overline{A}_g \) when \( n_b = 1 \) and \( t_{H,o} = -25^\circ C \) - a) and \( t_{H,o} = -35^\circ C \) - b).

The effect of the ratio of the sides of the projection of the building is characterized by a steady tendency to reduce thermal efficiency with an increase in the length of the building (at the constant heated volume and height) (figure 3). Although in this case the other factors have a significant impact on the rate of change of \( q_o \). Thus, with growth from 1 to 7, the increase is 14%, 11% and 5.5% for single-storey buildings with a volume of 500 m³, 1000 m³ and 5000 m³ at a relatively high estimated temperature.
For 4 and 7 storey buildings, these figures will be 27%, 23% and 13% respectively; 31%, 27, and 17%. For a region with colder climates, the rate of decline is slightly lower, but still quite noticeable:

- For single storey buildings: 13%, 10%, 5%;
- 4 storeys: 24%, 20%, 11.5%;
- 7 storeys: 28%, 24% and 15% (figure 3b).

Interestingly, as the volume of buildings increases, the distribution of specifics levels may change. For small buildings, the characteristic $q_o$ monotonously increases from a single-storey to a 7-storey building. And with the increase in volume to 5000 m³, the single-storey building is more efficient than a four-storey building. The same effect is also in compact ($n_b \leq (2.2 - 3)$) 1000 buildings m³.

Figure 5. Changing the specific heating characteristics of the building from the relative area of glazing $\bar{A}_o$ when $n_b = 7$ and $t_{H,o} = -25°C$ - a) and $t_{H,o} = -35°C$ - b).

One of the important characteristics of the building is the area of glazing of vertical surfaces $\bar{A}_o$. The effect of this indicator on the separate heating characteristic is presented in Figure 4, 5. For square in terms of buildings $n_b = 1$, 2.5 times increase in the area of translucent a spaces does not result in a significant change. The maximum increase was about 9% for the 500 m³ and 7.8 per cent for the compact building. In general, there is a tendency to reduce the impact of the degree of glazing on the thermal characteristic, while increasing the volume of the object and reducing the floor. At the same time, for more severe climatic areas, this impact is less significant than for warmer areas. So for significant compact buildings (5,000 m³) and $t_{H,o} = -35°C$ increase $q_o$ from just 1% (for single-storey buildings) to 2.5% (7 storeys), against 1.5% and 4.2% for . In addition, the larger the building, the more significant the difference in the thermal characteristics of small and high-rise buildings.

The results of the analysis presented by the thermal performance model of the heating system show a significant impact of volume-planning indicators on the efficiency of heat conservation. Although the regulatory requirements for insulation of fencing structures somewhat smooth the effect of choosing the optimal parameters of the building, but nevertheless the difference in the specific capacity of heating can reach more than 30% for buildings of the same volume, but different floors and configuration in the plan.

Of course, the purpose of the building's bulk-planning solutions is not always focused on achieving the highest energy efficiency, but the proposed model can help in the consideration and evaluation of options that meet both functional and energy-saving requirements.
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