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The effect of the aerodynamics of indoor air flows on the power of the heating system

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Abstract. An analytical dependence is presented for calculating the power of a heating system, taking into account the aerodynamics of the movement of air flows inside a heated room. The analytical dependence is derived on the basis of the theory of a two-zone mathematical model of a heated room. The method allows us to determine a rational way of organizing heating to ensure minimal transmission heat loss through enclosing structures, taking into account factors affecting thermal and air processes in a heated room and contributing to a decrease in the power of the heating system as a whole. The results of the analysis carried out on the regularity of the movement of air flows in a room divided into two control volumes (CV): upper and lower CV. A mathematical model of the processes of heat and mass transfer of a heated room in an administrative or residential building has been developed, which takes into account the heat exchange between the upper and lower CV. The physical picture of the distribution of air and heat flows in a heated room with a local heat source located in the window sill space of the heated room is analyzed. A method for calculating the power of the heating system is proposed, taking into account the nature of the aerodynamics of the distribution of air flows in a heated room. An analytical dependence for calculating the thermal power of a heating system is presented, taking into account the characteristics of the distribution of heat and air flows across two control volumes of the heated room.

Keywords: heating system power, air distribution, transmission heat loss, infiltration heat loss, flow aerodynamics, control volume

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1. INTRODUCTION

The annual costs for the installation and operation of heating systems in the premises of buildings for various purposes are very high. Therefore, the proposed method for calculating the power of heating systems for buildings of various purposes seems to be very relevant.

The problem of determining the power of heating systems has been sufficiently studied in the works [1-23]. The method of calculating the heating system capacity presented in the regulatory literature is quite accurate. The latter is based on the principle of heat balance for the heated room.

At the same time, the existing methods for calculating the capacity of the heating system of residential and public buildings are based on a single-zone model of the room and do not fully take into account the aerodynamic processes occurring in them. This leads to deviations of the air parameters in the working area of the room from the set values and an increase in the power of the heating system.

The paper presents an improved method for calculating the power of a heating system based on the position balance method, which takes into account all factors affecting the processes of heat and mass transfer. This helps to reduce transmission heat losses and improve the efficiency of the heating system.

Using numerical modeling in the ANSYS physical processes programming complex, experimental studies were conducted in an isothermal chamber of the Scientific and Educational Center for Heat, Gas and Ventilation at the University. (REC "TGV" NRU MGSU), allowed to identify patterns of movement of air flows in the room, as well as to develop a methodology for calculating the heating system, taking into account the heat exchange between the upper and lower CV.

The practical application of the proposed method of calculating the heating system will increase the efficiency of its operation, as well as affect the effectiveness of measures to improve the energy efficiency of buildings for various purposes.

Methods of organizing air distribution to reduce the amount of transmission and infiltration heat loss in a heated room are proposed. Recommendations for calculating transmission heat losses when calculating the heat consumption of a building during the heating period, taking into account the aerodynamics of air flows.

2. METHODS AND MATERIALS

One of the stages of calculation and design of heating systems is the calculation of heat loss. The thermal capacity of the heating system is determined for the harshest calculated part of the cold season. Since fences and rooms have thermal inertia, the average temperature of the coldest five days is taken as the calculated temperature.

The parameters characterizing the microclimate of the premises primarily include: temperature t_{in}, speed of movement v_{in}, and relative humidity φ_{in}. The sensations of a person in a room are also affected by the radiation temperature t_{rad}, ° C, which is calculated using the formula:

$$t_{rad} = \frac{\sum A_i \cdot \mathrm{t}_i}{\sum A_i} \,, \tag{1}$$

where A_i and t_i the area and temperature of the surface located in the room, m^2

The lowest value of the permissible room temperatures (t_{in}) is calculated in the process of determining the heat transfer coefficient of the external enclosing structure [1, 4].

The thermal engineering calculation of the external enclosing structures assumes that heat transfer occurs in stationary thermal conditions and is described by the Fourier equation:

$$q_t = -\lambda \frac{dt}{dx} , \qquad (2)$$

where q_t – is the heat flux passing through a unit area of a perpendicular surface, W/m^2; t - is the temperature varying along the x axis, °C, λ – is the thermal conductivity of the enclosing structure material, W/(m·°C);

Heat transfer can be carried out by thermal conductivity (Cd), convection (C) and radiation (R) (Fig. 1). In the process of heat exchange in a room, all its internal surfaces are involved: heated and cooled, air jets (streams) and room air [4].

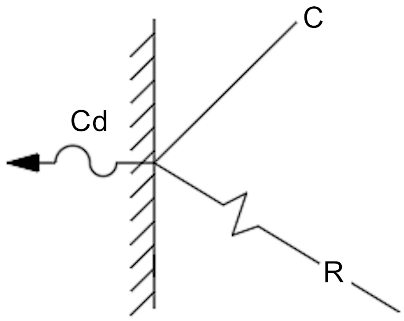

Fig. 1. Thermal balance of the surface [5].

The heat balance equation for any surface in a room (3) follows from the law of conservation of energy [4]:

$$R_i+C_i+Cd_i=0 . \qquad (3)$$

The necessary parameters of the air environment in the serviced or working area of the heated room.

In two control volumes (CV) of the room, the supply and removal of both air masses, heat, and other harmful emissions are observed. The boundary between the control volumes is represented by the plane of the control surface (KS). In the control volumes of the room, the processes of absorption and release of harmful substances occur simultaneously. The external environment can affect the control volumes through the boundaries of the control volume. The working or serviced area of the room, where the necessary air parameters are provided, is identified in operation as the lower control volume (lower CV) [1].

The area of the upper zone of the room is defined as the control volume in the upper zone of the room (upper CV), where the temperature can be varied vertically.

The areas of space in a heated room are conditionally divided into two volumes. The volume of the heated room is divided into two zones, the lower one as a working or serviced zone (lower CV) and the upper one – the remaining volume of the heated room (upper CV) [12].

The balance equations for consumption and energy are compiled.

The magnitude of the mass flows, taking into account their direction, is zero (Fig. 2).

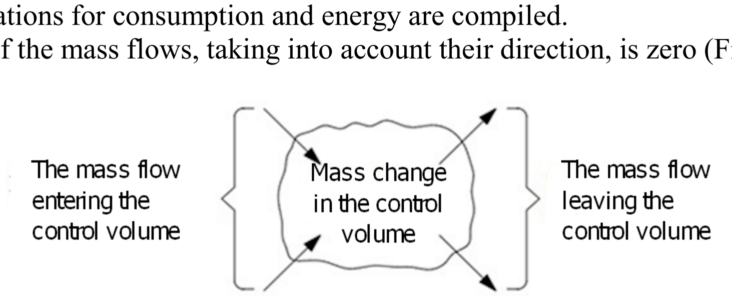

Fig. 2. The balance on the consumption of the conditional control volume.

The heat balance for the conditional control volume is reduced to thermal equilibrium. The amount of heat gain in the control volume is equal to the amount of heat loss from the control volume (Fig. 3).

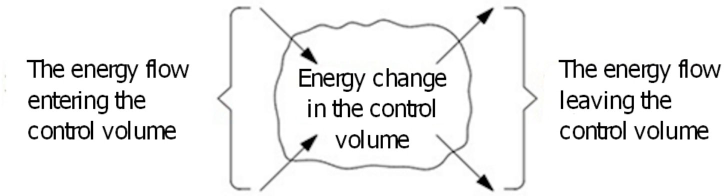

Fig. 3. The heat balance of the conditional control volume.

In general, the CV-s of a heated room are represented as a limited space inside a room with a linear heat source in the window sill space in the lower CV – $M(V_{LCV})$ and moving air flows G(V). The flows passing through various control surfaces (KP) in the work are designated as: M(A) – the heat released; G (A) – the masses of air flows.

The schematic diagram of heat and mass transfer processes in a room where the heating process is organized from a local heat source located in the volume of the lower zone is shown in Figure 4. The balance equations for heat and air consumption are as follows:

Balance equations drawn up for the upper control volume (upper CV):

$$\begin{cases} \int\limits_{V_{UCV}} G(V_{UCV})dV_{UCV} + \int\limits_{F_{UCV}} G(A_{UCV})dA_{UCV} = 0 \\ \int\limits_{V_{UCV}} M(V_{UCV})dV_{UCV} + \int\limits_{F_{UCV}} M(A_{UCV})dA_{UCV} + \int\limits_{V_{UCV}} G(V_{UCV})\Pi(V_{UCV})dV_{UCV} + \\ \quad + \int\limits_{F_{UCV}} G(A_{UCV})\Pi(A_{UCV})dA_{UCV} = 0 \end{cases} \quad (3)$$

Balance equations drawn up for the lower control volume (lower CV):

$$\begin{cases} \int\limits_{V_{LCV}} G(V_{LCV})dV_{LCV} + \int\limits_{F_{LCV}} G(F_{LCV})dA_{LCV} = 0 \\ \int\limits_{V_{LCV}} M(V_{LCV})dV_{LCV} + \int\limits_{F_{LCV}} M(A_{LCV})dA_{LCV} + \int\limits_{V_{LCV}} G(V_{LCV})\Pi(V_{LCV})dV_{LCV} + \\ \quad + \int\limits_{F_{LCV}} G(A_{LCV})\Pi(A_{LCV})dA_{LCV} = 0 \end{cases} \quad (4)$$

In the systems of equations (4 and 5), the first term of the first equations ($G(V_{UCV})dV_{UCV}$ and $G(V_{LCV})dV_{LCV}$) is the flow rate of air entering or leaving from various points of the CV (general exchange ventilation). In the second term of the same equation ($G(A_{UCV})dA_{UCV}$ and $G(A_{LCV})dA_{LCV}$) is the mass transfer between CV.

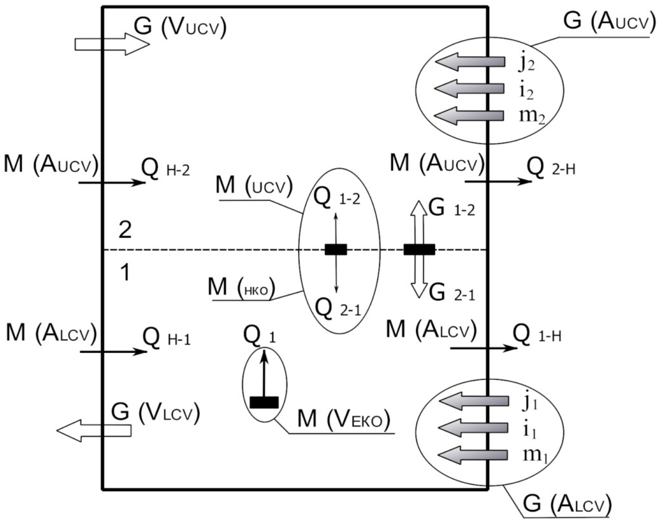

Fig. 4. Scheme of thermal and air processes in a heated room: 1 – lower control volume; 2 – upper control volume.

A mathematical model of thermal and air processes is considered for the most typical case of the scheme of organization of air exchange of a heated room in an administrative or residential building.

This case includes heated rooms where the supply air is supplied by laying jets to the upper control volume and removed from the lower control volume.

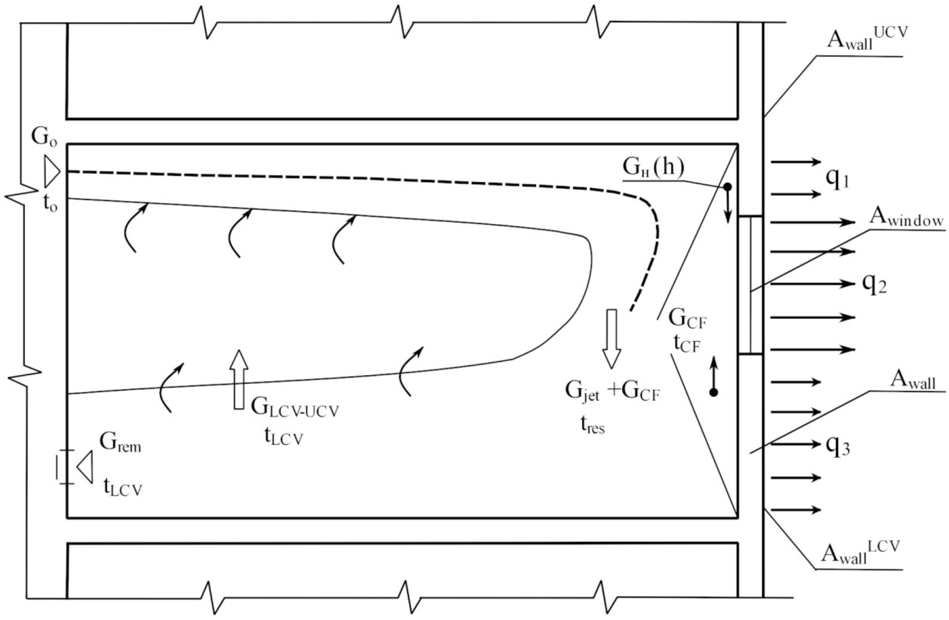

Fig. 5. Scheme of heat and mass transfer processes of a heated room with controlled aerodynamics.

A physical and mathematical description of the thermal and air processes occurring in a heated room (Fig. 5) can be presented as follows (6).

Air-heat balance for the lower control volume:

$$\begin{cases} G_{jet} - G_{LCV-UCV} - G_{rem} = 0, \\ G_{jet} \cdot t_{jet} \cdot c_{\text{air}} - (\beta - 1) \cdot G_{jet} \cdot t_{\text{LCV}} \cdot c_{\text{air}} + G_{rem} \cdot t_{\text{LCV}} \cdot c_{\text{air}} + Q_{HS} - Q_2^{\text{inf}} - Q_2^{tr} + Q^H = 0 \end{cases}, \quad (5)$$

where: G_{jet} – the amount of air in the jet coming from the upper to the lower CV; $G_{LCV\text{-}UCV}$ – the amount of air coming from the LCV to the UCV; Grem - the amount of air leaving the lower control volume zone; t_{jet} – the temperature on the axis line of the controlled jet at the upper boundary of the working or serviced area; t_{LCV} – the degree of air heating in the volume of the working or serviced area; c_{air} – specific heat capacity of air at constant pressure; Q_{HS} – the power of the heating system; Q_2^{tr} – transmission heat loss through the outer enclosing structures of the lower CV; Q_2^{inf} – transmission heat loss through the outer enclosing structures of the lower CV.

The amount of air flowing from the upper control volume to the lower control volume:

$$G_{LCV-UCV} = (\beta - 1) \cdot G_{jet} \ , \tag{6}$$

where: β is the coefficient of increase in the volume of air in the jet.

Transmission heat loss through the outer enclosing structures of the lower CV:

$$Q_2^{tr} = K \cdot A_2 \cdot (t_{\text{LCV}} - t_C^5) \cdot n \cdot (1 + \sum \beta) \ , \tag{7}$$

where: K is the heat transfer coefficient of the considered external enclosing structure in the lower CV area; A_2 is the area of the considered external enclosing structure in the lower CV area; t_{LCV} is the air temperature in the lower CV; n is the coefficient taking into account the location of the considered structure in the lower CV area relative to the external environment; **Σ**β is the total amount of additional heat loss; t_c^5 – the average temperature of a cold five-day period.

Infiltration heat loss through the outer enclosing structures of the lower CV:

$$Q_2^{\text{inf}} = G_{\text{inf}} \cdot A_2^{inf} \cdot (t_{LCV} - t_C^5) \cdot c_{air} \ , \tag{8}$$

where: G_{inf} is the amount of air infiltrating through the external enclosing structures located in the lower CV area; A_2^{inf} is the area of the considered external enclosing structure in the lower CV area; t_{LCV} is the air temperature in the lower CV; t_c^5 is the average temperature of a cold five–day period.

It follows from equation (6) that the power of the heating system, taking into account the geometric features of the jet entering the lower CV, can be determined as:

$$Q_{HS} = G_{rem} \cdot c_{\text{air}} \cdot t_{LCV} + (\beta - 1) \cdot G_{jet} \cdot t_{LCV} - c_{\text{air}} \cdot t_{jet} \cdot G_{jet} + Q_2^{\text{inf}} + Q_2^{tr} - Q^H \ , \tag{9}$$

where: Q^H is the value of household or technological heat supply.

Formula (10) is derived for premises of residential or public buildings in which air exchange (L_{pr}) is calculated according to the normative multiplicities of air exchange:

$$L_{np} = K_p \cdot V_{\text{room}} \ , \tag{10}$$

or according to sanitary standards:

$$L_{np} = L_{np}^{норм} \cdot N \ , \tag{11}$$

where: N is the number of people in the service area.

$$L_{np} = L_{np}^{норм} \cdot A \ , \tag{12}$$

where: A is the area of the living space.
From equation (6):

$$G_{rem} = G_{jet} - (\beta - 1) \cdot G_{\text{LCV-UCV}} \,, \tag{13}$$

where G_{jet} is defined as:

$$G_{jet} = \beta \cdot G_o \,. \tag{14}$$

Therefore

$$G_{rem} = \beta \cdot G_o - (\beta - 1) \cdot G_{LCV-UCV} \,. \tag{15}$$

The calculation of the power of the heating system, taking into account the thermal and air processes occurring in a heated room, can be determined by the following formula:

$$\begin{gathered} Q_{HS} = G_o \cdot c_{\text{air}} \cdot (t_{LCV} - t_{jet}) + K \cdot A_{\text{LCV}} \cdot (t_{LCV} - t_c^5) \cdot n \cdot (1 + \sum \beta) + \\ + G_{\text{inf}} \cdot A_2^{inf} \cdot (t_{LCV} - t_c^5) \cdot c_{air} - q \cdot A \end{gathered} \,. \tag{16}$$

The analytical dependence, which makes it possible to determine the thermal power of the heating system without taking into account the controlled aerodynamics of air flows inside the room, is as follows:

$$Q_{HS} = K \cdot A_{\text{LCV}} \cdot (t_{LCV} - t_c^5) \cdot n \cdot (1 + \sum \beta) + G_{\text{inf}} \cdot A_2^{inf} \cdot (t_{LCV} - t_c^5) \cdot c_{в} - q \cdot A \,. \tag{17}$$

Supply jet, at the entrance to the service area, injects a descending convective flow from the surface of the outer fence in the upper CV, as well as an ascending convective flow formed on the surface of the heater, and with the resulting jet temperature $t_{jet} > t_{LCV}$, extends to the lower CV (service area).

The resulting temperature of the supply jet at the entrance to the serviced area of the room is determined by the formula (19), which takes into account the air and heat balance in the area from the outlet of the air distributor to mixing with convective flows formed on the surface of the heater (Fig. 6).

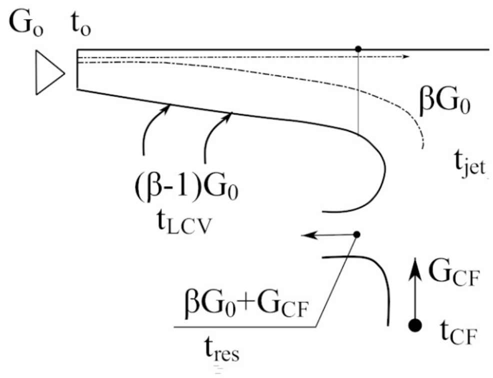

Fig. 6. Diagram of the supply jet in the area from its outlet from the air distributor to the entrance to the service area, during its mixing with convective flows formed on the surface of the heater.

$$\begin{cases} G_o \cdot (\beta - 1) + G_o + G_{CF} = \beta \cdot G_o + G_{CF}, \\ c_{air} \cdot t_{LCV} G_o \cdot (\beta - 1) + c_{air} \cdot t_o \cdot G_o + c_{air} \cdot t_{CF} \cdot G_{CF} = c_{air} \cdot t_{res} \cdot (\beta \cdot G_o + G_{CF}) \end{cases}. \quad (18)$$

The resulting air temperature at the entrance to the lower KV is determined from the heat balance equation:

$$t_{res} = \frac{G_o \cdot \left[t_{LCV} \cdot (\beta - 1) + t_o \right] + t_{CF} \cdot G_{CF}}{\beta \cdot G_o + G_{CF}}. \quad (19)$$

The temperature of the air flows flowing from the upper control volume to the lower one is more heated relative to the air in the working or serviced area, which follows from the expression (20).

Therefore, taking into account the aerodynamics of air flows in a heated room in accordance with equation (17) reduces the power of the heating system.

3. RESULTS AND DISCUSSION

The derived analytical formula (17) for calculating the power of the heating system takes into account the influence of the aerodynamics of air flows inside the room.

Based on the theoretical prerequisites for determining the characteristics of the formation of the resulting jet at the entrance to the service area, depending on the geometric characteristics of the supply jet, the temperatures of the heated and cooled surfaces, numerical studies were carried out in the ANSYS software package, shown in Fig. 7.

In the cold season, descending convective air flows form from the side of the cold surface of the window, and ascending convective flows form from the side of the heated heater. The supply air mixes with these convective flows and, with the resulting temperature, enters the lower part of the room (the working area of the room).

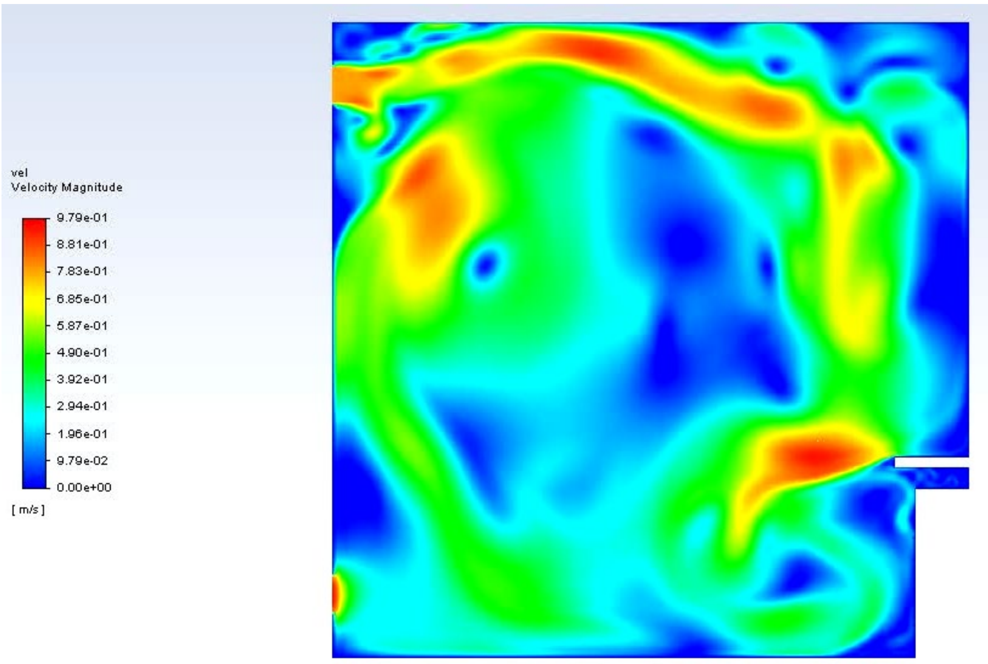

Fig. 7. Formation of a jet at the entrance to the service area with the resulting temperature depending on the geometric characteristics of the supply jet, the temperatures of the heated and cooled surfaces.

To verify the obtained analytical dependence on determining the power of the heating system, taking into account the aerodynamics of air flows (analytical formula 17), a full-scale experiment was conducted in the laboratory of the REC "TGV" NRU MGSU.

A local heat source in the form of a heating device was installed in the lower zone of the isothermal chamber under the cooled wall. The power of the heating system in the isothermal chamber was detected in the presence of controlled ventilation according to the "Top-down" scheme scheme, where the supply jet was directed by laying jets from an air distributor located on the opposite wall from the heater. When calculating the ventilation system, the flooring jet is supplied to the upper floor. It should be noted that when the air temperature in the working or serviced area remains relatively constant, it decreases in the volume of the upper zone. This leads to a decrease in transmission heat loss from the upper CV and the power of the heating system as a whole.

In the case when the calculation of the power of the heating system was carried out without taking into account the aerodynamics of air flows in a heated room, the general exchange ventilation system did not function. Experimental studies have shown that the gradient of air temperature change along the height of the heated room increases with an increase in the heat flow of the heater, which leads to an increase in transmission heat loss through the outer fences of the upper CV of the heated room, increasing the power of the heating system as a whole.

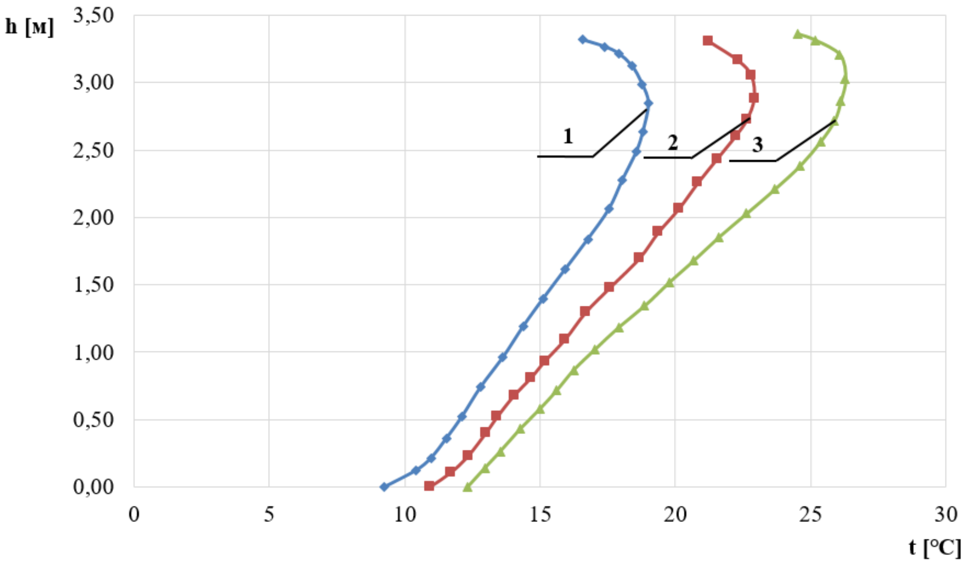

Fig. 8. Distribution of air temperature along the height of the heated room, without taking into account the aerodynamics of air flows in the room, depending on the heat flow of the heating device.

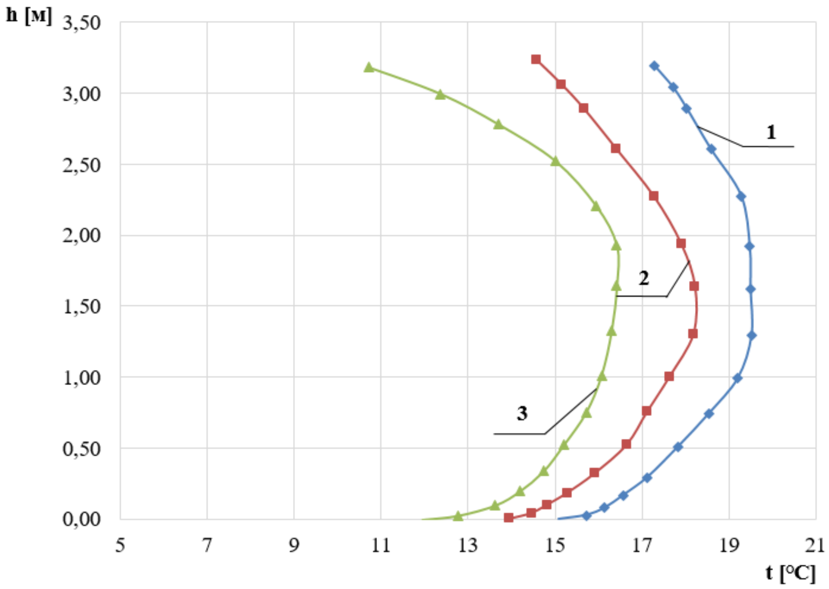

Fig. 9. Distribution of air temperature along the height of the heated room, taking into account the air distribution by laying jets according to the "Top-down" scheme, depending on the heat flow of the heating device: 1- q= 1000 W; 2- q= 800 W; 3- q=600 W.

Verification of the developed method was carried out under field conditions. To identify the dependence of the power of the heating system on the outside air temperature, taking into account the aerodynamics of the movement of air flows indoors under the influence of a controlled jet, organized according to the "Top-down" scheme and without taking into account the influence of the jet, a full-scale experiment was conducted. The results of the field experiment showed that taking into account the influence of controlled aerodynamics when calculating heating power reduces the desired value of heat flow to 7%.

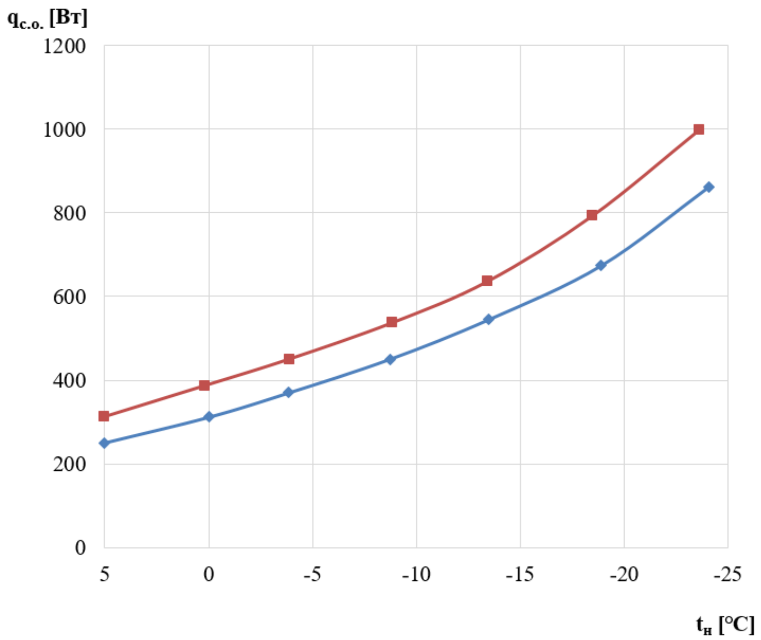

Fig. 10. The power of the heating system depends on the outside air temperature: rhombus – taking into account the controlled aerodynamics of air flows; square – without taking into account the controlled aerodynamics of air flows.

The results of the field experiment confirmed that the developed method of calculating the power of the heating system, based on the method of position balance, is reliable and can be used in solving engineering problems.

The conducted experiment in full-scale conditions revealed that taking into account the controlled scheme of air flow reduces the power of the heating system, depending on the outdoor temperature, by up to 7%.

4. CONCLUSIONS

The conducted literature review allows us to conclude that the existing methods for calculating the capacity of the heating system of residential and public buildings are based on a single-zone model of the room and do not fully take into account the aerodynamic processes occurring in them. This leads to deviations of the air parameters in the working area of the room from the set values and an increase in the power of the heating system.

The paper presents an improved method for calculating the power of a heating system based on the position balance method, which takes into account all factors affecting the processes of heat and mass transfer. This helps to reduce transmission heat losses and improve the efficiency of the heating system.

The formula obtained analytically to determine the power of the heating system takes into account the thermal and air processes in the heated room and is equally accurate for rooms with different ways of organizing air exchange.

The results of numerical modeling in the ANSYS software package, as well as the results of field experiments, confirmed that the developed method for calculating the power of the heating system is reliable and can be used to solve engineering problems.

The power of the heating system depends on the type of jet and the air distribution scheme.

When calculating the power of the heating system, taking into account the aerodynamics of air flows in a heated room, the power of the heating system relative to the traditional calculation method is reduced to 7%, depending on the scheme of organization of air exchange.

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