Calculation of room temperature drop after an emergency shutdown of heating

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Abstract. The method of calculating the cooling rate of a room when the heating system is turned off there is an important practical task. As a result of such calculation, the time within which the room will cool down to an acceptable temperature, is indicated. During this time, emergency brigades must restore heating in the building. The aim of the work is to provide some refinement of the existing fundamental calculation formula by taking into account additional factors affecting the cooling process of the room. These include: taking into account the time of the initial irregular cooling process, taking into account the heat storage capacity of internal enclosing structures and furniture or equipment in the room, consideration of the initial temperature conditions in external and internal enclosing structures when calculating their heat capacity. The proposed approximate engineering technique is verified by comparing the calculation results with the results of direct calculation by the numerical method of the non-stationary thermal regime of the room in the full statement.

1 Introduction

The modern centralized heat supply system in Russia has a relatively low degree of reliability, and as a result is characterized by a high frequency of emergency disconnections of subscribers. The proposed work is aimed at clarifying the time interval for the elimination of an emergency.

The task of cooling the premises of the building when the heat supply is stopped during the cold season has been solved for a long time and still retains its relevance due to the fact that it is directly related to ensuring the safety of people and structural elements of the building. The requirements of regulatory documents are mainly reduced to preventing a decrease in the minimum air temperature when eliminating accidents on heat supply systems below a certain level. For example, in SP 60.13330.2020 "Heating, ventilation and air conditioning SNiP 41-01-2003 (as amended, with Amendment # 1)" for residential premises, it is not allowed to reduce the air temperature below 15 °C. For residential premises of high-rise buildings in case of emergency termination of heat supply in SP 253.1325800.2016 "Engineering systems of high-rise buildings (with Amendment # 1)", in addition to limiting

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the minimum indoor air temperature of 15 °C, a requirement is introduced that allows lowering the air temperature to the specified value for no more than 54 hours.

It should be noted that in all works, which consider the cooling of the building, one of the tasks is to determine the change in room temperature after the building heat supply termination. However, approaches to solving this problem are different. We will consider the problem with no regard for the internal heat generation.

E.Ya. Sokolov was one of the first in the Soviet Union to propose a formula for calculating temperature changes up to the set ones during the room cooling $t_{in,z}$, °C [1]:

$$t_{in,z} = t_{out} + \frac{t_{in,0} - t_{out}}{e^{z_t/\beta}} \tag{1}$$

where $t_{in,0}$ is the initial (design) indoor air temperature of the room, °C;

t_{out} – outdoor air temperature, °C;

z_t – the time elapsed from the moment the heat supply was turned off until the indoor air temperature was reached $t_{in,z}$, h;

β – the accumulation coefficient of the building, h.

In the formula (1), the building current temperature depends on the accumulation coefficient of the building, and it is assumed that the rate of drop in the temperature of the indoor air will decrease depending on the current value of this temperature. An important provision of the formula (1) is the statement of the temperature change according to the exponential law.

The calculation of the room indoor air temperature during cooling and the cooling time was proposed by V.N. Bogoslovsky [2] using a formula written with the same notation values as the formula (1):

$$e^{-az_t} = \frac{t_{in,z} - t_{out}}{t_{in,0} - t_{out}} \tag{2}$$

In fact, this is the same formula as the (1) one. However, the accumulation coefficient β of the building has been replaced by the cooling rate indicator *a*, for which the values for buildings with of outdoor enclosing structures made of various structural elements are given from experimental studies.

The indicator of the cooling rate is the inverse value of the coefficient of thermal accumulation:

$$a = \frac{1}{\beta} \tag{3}$$

The accumulation coefficient β and the rate of the building cooling *a* are the parameters, which characterize the heat storage properties of the building. Moreover, only the heat capacity of the outer walls is taken into account. The accumulation coefficient is applied in the formula used for the heat supply [1]:

$$\beta = \frac{(c\rho A\delta)_{out.w}}{2} \frac{1}{qV} \tag{4}$$

where c, ρ, A, δ – respectively, are the specific mass heat capacity, kJ/(kg·°C); density, kg/m^3; area, m^2; and the thickness of the outer wall (enclosing structure), m;

V – the volume of a room or a building by external measurement, m^3;

q – specific thermal characteristics of a room or a building, determined by the formula, W/°C:

$$q = \sum kA \tag{5}$$

where $\sum kA$ is the sum of the products of the heat transfer coefficients and the areas of individual external enclosing structures (walls, windows, floorings) in a room or a building, W/°C.

If E.Ya. Sokolov paid more attention to the practical application of his formula, V.N. Bogoslovsky supplemented his reasoning with a consideration of the thermophysical cooling processes of the building, which have practical significance. So, he drew attention to the fact that not only the temperature difference between indoor and outdoor air decreases, but also "the values of the indicator *a* change somewhat over time, which is associated with a decrease in the coefficients of convective and radiant heat exchange with a lowering temperature, which significantly affect the rate of the room cooling."

Yu.V. Kononovich was one of the first who proposed to take into account the heat capacity of internal enclosing structures in the coefficient of thermal accumulation.

The proposed formula has the form [3]:

$$\beta = \frac{k_t \sum \delta_i \cdot c_i \cdot \rho_i \cdot F_i / 2}{3.6\left[\sum k_j F_j + L(c \cdot \rho)_{air}\right]} \tag{6}$$

where k_t is the correction factor for calculating the heat storage capacity of various enclosing structures, taking into account the heating method [3];

δ_i, c_i, ρ_i and F_i are the thickness, m; specific mass heat capacity, kJ/(kg·°C); density, kg/m^3; and the area of the *i*-th room enclosing structure, m^2;

k_j и F_j – heat transfer coefficient, W/(m^2·°C); and the area of the *j*-th enclosing structure, m^2;

L – infiltration air rate, m^3/h;

c_{air} and ρ_{air} – are specific mass heat capacity, kJ/(kg·°C); and infiltration air density, kg/m^3.

In foreign practice, the heat storage capacity of buildings is used, as a rule, to reduce energy consumption due to the accumulation of heat and cold from the environment (solar radiation, nighttime decrease in outdoor air temperature, etc.). With an excess of heat, accumulation (accumulation) occurs, with a shortage, return. For the effective accumulation of heat/cold, provided that the internal air temperature is maintained within the normalized values, enclosing structures have been proposed, which include substances with a phase transition [4-13]. In the case of intermittent operation of heating (cooling) systems, the heat storage capacity is directly taken into account to improve the accuracy of calculations [11-12]. In addition to energy-saving measures, in buildings with electric heating, heat accumulation by fences makes it possible to lower the peak power of power plants [13]. Much attention is paid to improving thermal comfort for people's stay and reducing energy consumption [14-21]. Numerical methods are used to solve the non-stationary thermal regime of premises, but within the framework of periodic thermal effects for the analysis and evaluation of energy consumption [11-15]. The issue of reducing the cooling capacity due to the accumulation of cold by a reinforced concrete slab during the night mode of operation of the natural ventilation system is considered [19].

To help designers, there is an International Standard ISO 1379 [22], where provision is made of a technique consisting in the fact that in order to determine the cooling time of a room to a certain temperature, it is necessary to know in advance the heat capacity of that part of the enclosing structures that has cooled during this time. To bring the calculation results closer to reality, the standard provides tables for various building materials.

The purpose of the work is to improve the accuracy of the results obtained according to the existing formulas for calculating the room cooling time after the heat supply has been stopped.

2 Methods

To achieve this goal, first of all, a program was developed for calculating the room non-stationary thermal mode a finite-difference explicit form using the *Excel* software package. In this case, the non-stationary process is divided into a set of stationary ones with a certain time step (Δz) for calculating one stage (the method of approximate numerical iteration [16]).

The algorithm of the program takes into account the following components of the thermal balance of the room: heat flow leaving through external enclosing structures; heat flow from internal enclosing structures and furniture (the furniture was not taken into account in these calculations) of the room; heat and/or cold precipitation from internal sources (not used in these calculations); heat introduced and removed by ventilation and infiltration air.

At the same time, it is taken into account that the infiltration air consumption decreases due to a lower temperature difference between the indoor and outdoor air over time. The coefficients of convective and radiant heat transfer on the internal surfaces of external and internal enclosing structures at each time step were recalculated taking into account the decrease in the temperature of the internal air and the internal surfaces of the enclosing structures. The heat transfer through the window was considered stationary at each step.

Verification of the calculation algorithm using an explicit finite-difference scheme was performed by comparing the calculation results with the results obtained according to the program available at the Chair of HGV based on an implicit finite-difference scheme. According to this program, the results of calculating the cooling of buildings were obtained and published in the Russian language.

Having analyzed the results of numerical solutions for cooling of rooms with various enclosing structures and room geometric parameters, the following additions are proposed to be made to the existing calculation methods. A parameter has been added to the exponential cooling equation that takes into account a sharp initial drop in the indoor air temperature when the heat supply is stopped. As a result, the description of the drop in the temperature of the room indoor air starts from the beginning of the regular cooling process:

$$\theta = \beta_0 \cdot e^{-\frac{z_L}{\beta}} \tag{7}$$

where θ – relative excess indoor air temperature $\theta = \dfrac{t_{in,z} - t_{out}}{t_{in,0} - t_{out}}$;

β_0 – a coefficient that takes into account the irregularity of the cooling process of the room (building) indoor air in the initial period of time. For residential premises of the apartment buildings with the current level of thermal protection in accordance with the requirements of SP 50.13330.2012 "Thermal protection of buildings. Updated version of SNiP 23-02-2003 (with Amendments # 1, 2)" (hereinafter SP 50) the value has been determined by approximating numerical results and makes within the limits $\beta_0 \approx 0.965\ldots0.935$ (in further calculations, the 0.95 value has been taken). Larger values of the coefficient correspond to the rooms with a larger area of internal enclosing structures and lower heat losses through external enclosing structures and heating of infiltration air.

Consequently, the coefficient β_0 shows the value of the relative excess temperature of the indoor air (at t = 0 h), at which the cooling process of the air becomes regular. If the coefficient β_0 is assumed to be equal to one, as it was in the original formulas, then the results

of the room cooling time will be overestimated. This is influenced by the air irregular cooling process in the initial period of time: there is a sharp drop in temperature by 1...2.5 °C, which is observed within 5 to 16 minutes after the heating system is turned off (complete cessation of heat supply). It is for this reason that it is impossible to consider the air cooling mode in the initial period of time as regular (at $\beta_0 = 1$), since the time of changing the room air temperature by 1 °C will be calculated for hours, which is not really the case. V.N. Bogoslovsky also wrote about a sharp decrease in the air temperature when the heat supply in the room is stopped or partially changed in [2].

The indicator of the room thermal accumulation is proposed to be determined by the refined formula:

$$\beta = \frac{\sum_{i=1}^{n} C_{in.enc,k} \Big/ 2 + \sum_{j=1}^{m} C^{\theta}_{out.enc,j} + C_{in.fill} + C_{air}}{\sum_{j=1}^{m} A_{out.enc,j} \dfrac{1}{R^{red}_{out.enc,j}} + G_{inf} c_{air} \varphi_{inf}} \tag{8}$$

where $C^{\theta}_{out.enc,j}$ – the reduced heat capacity of the *j*-th external enclosing structure of the room, determined by the stationary temperature distribution in the thickness of the enclosing structure at the difference between the outdoor and the initial indoor air temperature before switching off the heating system, J/°C (Fig. 1). Is determined by the formula:

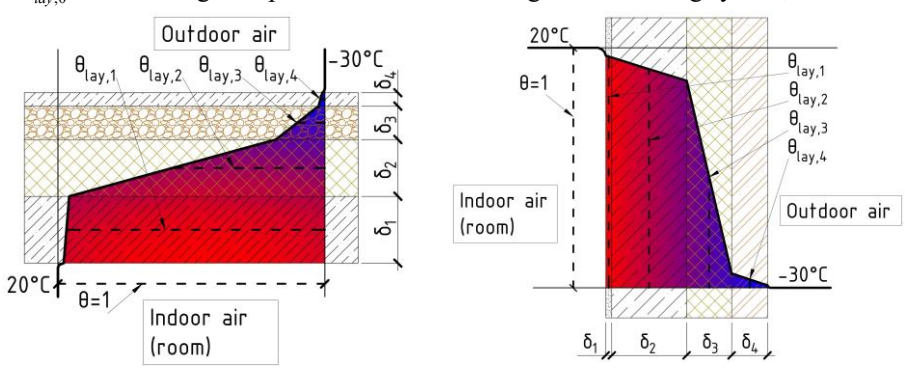
$$C^{\theta}_{out.enc} = \sum_{i=1}^{n} C_{lay,i} \theta_{lay,i} \tag{9}$$

where $C_{lay,i}$ – the heat capacity of the *i*-th layer of the outer enclosing structure, J/°C;

$\theta_{lay,i}$ – the relative excess temperature of the *i*-th layer of the external enclosing structure at the initial moment of time with a stationary temperature distribution, determined by the formula:

$$\theta_{lay} = \frac{t_{lay,0} - t_{out}}{t_{in,0} - t_{out}} \tag{10}$$

where $t_{lay,0}$ – the average temperature before switching off the heating system, °C.



a) b)

Fig. 1. The reduced heat capacity of external enclosing structures
a – the coating of the building; *b* – the outer wall

$C_{in.enc,k}$ – the heat capacity of the *k*-th internal enclosing structure of the room (partition, floor or ceiling), J/°C. The division by 2 of the heat capacity of internal enclosing structures is due to the assumption that all rooms of the building are in the same cooling conditions after the heat supply is turned off. Therefore, only half of the heat capacity of each internal enclosing structure belongs to the room under consideration [3]. Since the internal enclosing structures have an initial temperature approximately equal to the initial temperature of the room air, their heat capacity is determined by the formula (9), where $\theta_{lay,i} = 1$ for all layers (Fig. 2);

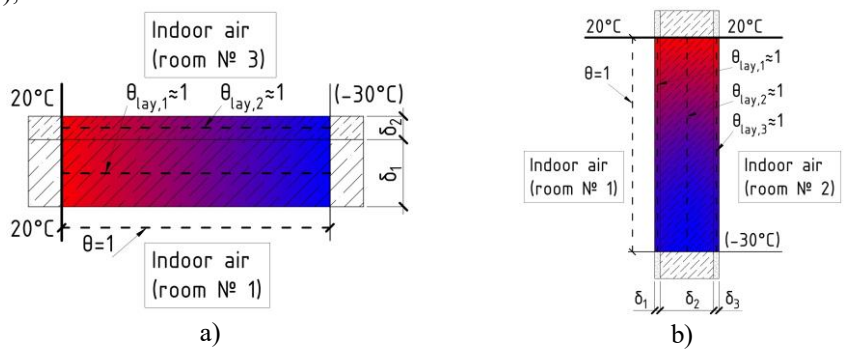


Fig. 2. Reduced heat capacity of internal enclosing structures: a – floor overlap; b – partitions

$C_{in.fill}$ – the heat capacity of the room utilities (interior furniture and equipment), J/°C. The temperature of the interior furniture and equipment of the room also approximately is equal to the initial air temperature. Consequently, the heat capacity $C_{in.fill}$ is determined by analogy to the formula (9), where $\theta_{lay,i} = 1$;

C_{air} – the heat capacity of the indoor air of the room at the initial time before switching off the heating system, J/°C;

$A_{out.enc,j}$ and $R^{red}_{out.enc,j}$ – respectively, are the area, m^2; and the reduced heat transfer resistance of the room *j*-th external enclosing structure, (m^2·°C)/W;

G_{inf} and c_{air} – flow rate, kg/s; and heat capacity of the infiltration air, J/(kg·°C);

φ_{inf} – the coefficient of lowering the heat flow for heating the infiltration air, due to a decrease in hydrostatic pressure during the cooling of the room and, as a consequence, a decrease in the flow of infiltration air. Determined by the formula:

$$\varphi_{inf} = 0.5\omega_{stat} + \omega_{dyn} \tag{11}$$

where ω_{stat} and ω_{dyn} – the proportions of static and dynamic pressures in the available pressure forming infiltration:

$$\omega_{stat} = \frac{\Delta P_{stat}}{\Delta P_{total}}; \quad \omega_{dyn} = \frac{\Delta P_{dyn}}{\Delta P_{total}} \tag{12}$$

ΔP_{stat} – the value of the hydrostatic pressure at the initial temperature difference of the outside and inside air before the termination of the heat supply, Pa;

ΔP_{dyn} – the value of dynamic pressure, Pa;

ΔP_{total} – the full pressure (the sum of static and dynamic pressures) inducing infiltration, Pa.

The heat capacity of windows in the formula of the coefficient of thermal accumulation (8) is not taken into account, due its small value. However, it is possible to take it into account in a similar way as the heat capacity of the outer wall.

The formula of the coefficient of thermal accumulation (8) is derived from the differential equation of the thermal balance of indoor air with a number of assumptions formed during the analysis of the results of numerical solutions.

To verify the accuracy of the results obtained according to the cooling refined formulas (7) and the coefficient of thermal accumulation (8), a comparison was made with the results obtained by direct calculation according to the developed calculation program described above (Table 1).

The outer wall is three-layered one with effective insulation and brickwork cladding. The sequence of layers (from inside to outside): a plaster layer of thickness δ = 20 mm, thermal conductivity λ = 0.87 W/(m·°C), density ρ = 1700 kg/m^3; structural layer of reinforced concrete δ = 200 mm, λ = 2.04 W/(m·°C), ρ = 2500 kg/m^3; insulation made of mineral wool slabs δ = 200 mm, λ = 0.045 W/(m·°C), ρ = 80 kg/m^3; facing brick δ = 120 mm, λ = 0.58 W/(m·°C), ρ = 1400 kg/m^3.The total thermal resistance of the outer wall is 4.813 (m^2·°C)/W. The window's heat transfer resistance is 0.5 (m^2·°C)/W; the transverse air permeability is 2.75 kg/(m^2·h).

The flooring consists of a reinforced concrete slab δ = 200 mm, λ = 2.04 W/(m·°C), ρ = 2500 kg/m^3; cement-sand screed δ = 70 mm, λ = 0.93 W/(m·°C), ρ = 1800 kg/m^3.The partitions have the same plaster layers on both sides δ = 20 mm, λ = 0.87 W/(m·°C), ρ = 1700 kg/m^3.The thickness of the inter-apartment partition is made of aerated concrete block D600 δ = 200 mm, λ = 0.26 W/(m·°C), ρ = 600 kg/m^3; the interior partition is made of gypsum rectangular blocks with grooves and ridges on opposite edges δ = 100 mm, λ = 0.43 W/(m·°C), ρ = 1000 kg/m^3. The specific mass heat capacity of the materials of the enclosing structure layers is adopted according to Appendix T of SP 50.

The boundary and initial calculation conditions:

- the initial room air temperature is 20 °C; the outdoor air temperature is -30 °C (*const*); the temperature of the coating, flooring and partitions is 20 °C; the initial temperature distribution in the outer wall corresponds to a stationary one at the specified internal initial and outdoor air temperatures;
- the heat transfer coefficient on the outer surface of the wall is 23 W/(m^2·°C); the heat transfer coefficient on the internal surfaces is calculated for each iteration depending on the temperature difference between the surface and the internal air (convective part), the radiant component is assumed constant;
- the rate of the air cooling in adjacent rooms (behind internal enclosing structures: partitions, flooring and roofing) is equal to the cooling rate of internal air in the design room.

3 Results

The average temperature deviation in modulus was 0.2 °C during the cooling interval of the room from 20 °C to -5 °C, while the elapsed time from the moment when the heating system was switched off made 294.3 hours (Table 1).

Table 1. Cooling time of the room under investigation

Time from the moment when the heating system was switched off, h	Indoor air temperature, °C		Temperature deviation relative to the numerical solution, °C
	Numerical solution	According to refined formulas	
7.5	17.50	16.73	0.77
17.1	16.25	15.76	0.49
28.0	15.00	14.69	0.31
39.6	13.75	13.57	0.18
51.8	12.50	12.43	0.07
64.7	11.25	11.26	-0.01
78.1	10.00	10.07	-0.07
92.1	8.75	8.87	-0.12
106.6	7.50	7.66	-0.16
121.8	6.25	6.43	-0.18
137.6	5.00	5.20	-0.20
154.1	3.75	3.96	-0.21
171.4	2.50	2.70	-0.20
189.4	1.25	1.44	-0.19
208.4	0.00	0.17	-0.17
228.2	-1.25	-1.10	-0.15
249.1	-2.50	-2.38	-0.12
271.1	-3.75	-3.68	-0.07
294.3	-5.00	-4.97	-0.03

To improve the visual perception of the results, according to Table 1, graphs of changes in the indoor air temperature of the room have been constructed using two calculation methods (Fig. 3).

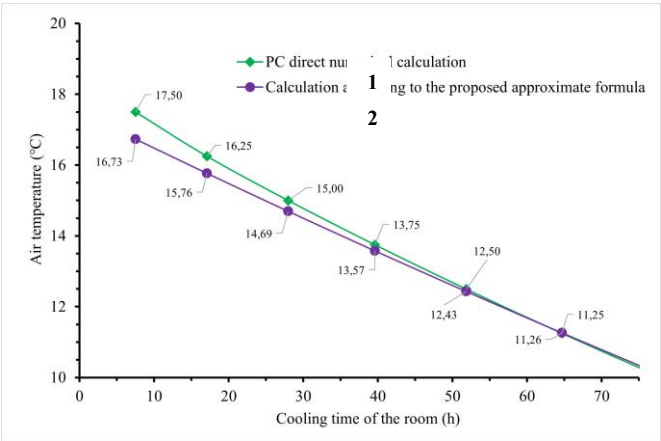


Fig. 3. Cooling time of the room under investigation: 1 – PC direct numerical calculation, 2 – calculation according to the proposed approximate formula

It should be noted that the greatest deviation of the results is observed in the time interval from the moment the heat supply to the premises is stopped up to ≈ 20 hours, which is due to the influence of the irregular cooling process of the internal air and the internal surfaces of the enclosing structures at the initial moments of time. However, the accuracy of the results is still within ±1°C. Further, the obtained results of the indoor air temperature have a deviation of less than ±0.2 °C.

After 75 hours from the moment of switching off the heating system, the indoor air temperature of the room decreased from 20 °C to ≈ 10.3 °C, while the infiltration air consumption decreased from 6.88 kg/h to 5.64 kg/h (at $\omega_{dyn} = 0.1$).

4 Discussion

The given example confirms that the proposed formula for determining the coefficient of thermal accumulation of a room really takes into account the influence of the internal and external heat resistance of the room enclosing structures. In this case, the external (throughout) heat resistance of the wall is taken into account using the reduced heat capacity, which reflects the actual value of the accumulated amount of heat. It helps to slow down the cooling process of the indoor air of the room (building) after the heating system is turned off. Similarly, the reduced heat capacity of the building roofing is determined for the rooms of the last floor, where the ceiling is the inner surface of the outer covering**.**

It should be noted that the developed strict algorithm for determining the reduced heat capacity of external multilayer enclosing structures allows us to take into account the following factors affecting the amount of accumulated heat by the enclosing structure:

1. Location of the thermal insulation layer. In the case of internal insulation of the enclosing structure (before the structural layer), it is intuitively clear that the amount of accumulated heat by the most heat-intensive structural layer cannot equal the value obtained with classical external insulation (after the structural layer), which is also confirmed by the results obtained in [19]. Indeed, the value of the relative excess temperature of the structural layer (formula (9), in the case of internal insulation, will be low. Consequently, the reduced heat capacity of an external multilayer enclosing structure with the internal insulation will be much less, compared to a similar enclosing structure with the external insulation (formula (8).
2. The thickness of the thermal insulation layer. With an increase in the thickness of the thermal insulation layer, the average temperature of the structural layer (with external insulation of the structure) increases. Thus, the developed method allows us to take into account not only the increase in the overall resistance to heat transfer of the outer enclosing structure, but also an increase in the accumulated amount of heat, which directly affects the cooling rate of the room (building). With an increase in the thickness of the insulation in the enclosing structures with internal insulation, the accumulated amount of heat decreases.

The product of the area and the heat transfer coefficient of the outer enclosing structure $A_{out.enc}\dfrac{1}{R^{red}_{out.enc}}$ (hereinafter, the total heat transfer coefficient) in the formula of the heat accumulation coefficient (7) has no reducing coefficients, since the outer enclosing structure during the cooling of the room gives heat to the external environment with a constant intensity equal to the value of the total heat transfer coefficient. This situation is explained by a slight change in the temperature of the outer surface of the structure during cooling, which is confirmed by the numerical solution of the problem.

Consequently, the outer enclosing structures influence the cooling rate of the room (building) by means of two factors:

- the magnitude of the total heat transfer coefficient characterizing the heat-protective qualities of the enclosing structure;
- the values of the reduced heat capacity characterizing the heat storage capacity of the enclosing structure.

5 Conclusion

1. The parameter added to the exponential cooling equation by E.Ya. Sokolov and V.N. Bogoslovsky takes into account the sharp initial drop in the indoor air temperature after the heating system is turned off.
2. A formula for calculating the coefficient of thermal accumulation is proposed, taking into account the heat resistance of internal and external enclosing structures and the heat capacity of the room utilities, as well as reducing the consumption of infiltration air during cooling.
3. A strict algorithm has been developed for calculating the heat storage capacity of external multilayer enclosing structures as part of the cooling process of a room (building).
4. The proposed additions provide an average deviation in modulus of the results of the internal air temperature during the cooling of the room within 0.2 ℃, relative to the results of a direct numerical solution.

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