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Non-stationary thermal mode of a room at integrated regulation of split systems

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Abstract. Due to the non-linearity of the propagation of temperature waves in massive fences, one of the most difficult control objects is an air-conditioned room equipped with automated microclimate systems, especially if complex algorithms are used for regulation. Therefore, the task of studying the non-stationary thermal regime of such a room still remains actual, despite the presence of a number of solutions describing the behavior of the air temperature in it with changes in heat supply. On the other hand, such objects are regularly found in the decision-making process to ensure an internal microclimate, so the results obtained can be used for a wide class of tasks. The proposed work presents a variant of a simplified mathematical formulation and solution of the task of calculating changes in internal temperature in a room in which a local split-system type cooling system is provided for the assimilation of heat surpluses, regulated by an integral law, in conditions when general exchange ventilation performs only sanitary and hygienic functions. The basic differential equation of the room thermal balance for this case is formulated, and it is shown that with the introduction of a fixed layer thickness of sharp temperature fluctuations over the considered time interval, this equation with feedback describing the action of the regulator is linear of the second order and is solved in elementary functions in the form of a damped sine wave. Using this solution, calculations were performed for a characteristic room and its validity and formal compliance with the classical results of the automatic control theory were proved by comparing the results with data from field measurements carried out in the same room, as well as with the results obtained for similar tasks by other authors. The obtained formulas are proposed to be used for estimated calculations of the indoor air temperature behavior in an air-conditioned room with the assimilation of heat supply by split systems regulated by an integral law, and for solving identification problems to determine the actual parameters of the room and the controller.

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1. *Introduction*

The object of the proposed publication study is the nature of changes in indoor air temperature over time in conditions of intermittently changing heat supply, if this room is serviced by a local cooling system regulated by an integral law, and general exchange ventilation performs sanitary and hygienic functions and is not directly involved in temperature stabilization.

An analysis of the information available in various sources, representing both scientific articles and monographs, educational and regulatory reference literature, allows us to note that research work related to the assessment of non-stationary heat and humidity processes and changes in the concentration of harmful substances in premises, as well as the mode of operation of equipment of microclimate systems serving them and their technical means automation has developed in parallel in several directions. One of them is the consideration of processes occurring directly in the air environment of a room and the material of its enclosing structures under various kinds of variable thermal influences, including harmonic or discontinuous ones. Several engineering and analytical methods that have become most famous in the design practice have been created here, for example, the "response factor" method, the theory of thermal stability, as well as a number of others, especially concerning the calculation of lowering the temperature in a building in case of failures of heat supply systems or, conversely, heating its premises in case of excessive heat supply or additional heat from others sources, for example, [1–3]. Within the framework of such calculations, individual characteristics of building microclimate systems can also be taken into account, but their role in this approach is mainly reduced to issues of their participation in the total thermal balance of the building, that is, in terms of the heat amount that enters or is removed from the premises due to the operation of these systems. In some cases, especially when it comes to optimization issues, which may be typical primarily for heating and heat supply systems, as well as when choosing the level of thermal protection of enclosing structures, economic methods may also be involved, however, such work most often has the disadvantage that their results are of a private nature and are not generalized to other cases [4]. The improvement of information technologies contributes, of course, to the fact that engineering and analytical methods are gradually supplemented, and in some cases replaced by numerical ones, although this is still more typical for foreign publications, in particular [5, 6], which, however, in addition to the actual numerical calculations, also include experimental ones data, making it possible to identify the constructed models, which, of course, is the advantage of these publications.

The second area of research concerns the study of heat exchange processes in equipment for processing supply air or in heaters of heating and hot water supply systems. Traditionally, more specific methods have been used here, based on the equations of thermal balance and heat transfer, including in differential form, and using dimensionless parameters, in particular, in the same works [1, 2], but without direct connection with the room and automation equipment, although it is easy to see that in fact, they are a single system. The third direction covers issues of regulation of microclimate systems and their control, and it was characterized by consideration of the relevant processes from the point of view of the automatic control theory, which is based on the concepts of the system links and formal connections between them on the principle of a "black box", which in some cases causes neglect of the physical essence of the observed phenomena. In order to obtain results acceptable in engineering practice, these links are mainly considered as linear ones, which often causes significant simplifications and omission of key transient processes in premises features [1, 2, 5, 6], what will be clear from the following. The consequence of such a separate consideration of, in fact, significantly related phenomena is an increase in the number of works where the features and behavior of a particular object are studied, for example, for underground structures in harsh climatic conditions [7] and external fences with heat-conducting inclusions [8]. Here, we can also mention an earlier article by the author of this work [9], which presents an engineering and analytical dependence of the velocity of movement of the front of a temperature disturbance in the thick wall of a hollow round cylinder. It can also be noted that the authors of some other publications, in particular [10, 11], on the contrary, focus on identifying the initial data and characteristics, for example, the actual thermophysical properties of building materials based on the results of their temperature behavior measured by one method or another under various conditions, that is, they actually make attempts to solve problems, which are the reverse of those discussed above, but this also applies to individual specific objects.

If numerical methods are involved in the solution, in some cases, it makes it possible to build a comprehensive model that includes all the listed systems and factors, but the very specificity of such approaches, as a rule, does not make it possible to obtain universal engineering and analytical techniques that would be acceptable for engineering practice and evaluation calculations, as well as for implementation into the educational and normative reference literature, since it requires an individual calculation on a computer for each individual object. In addition, the operation of the corresponding programs may require a large amount of initial data in the form of room parameters and their engineering systems [12, 13], since the algorithms under consideration require careful consideration of boundary conditions when calculating temperature fields. Another algorithm, developed in [14] and using quite a lot of parameters as input data for simulating transients, nevertheless contains a serious limitation in terms of its applicability, since it requires the mandatory presence of a working heating system. It should be noted here that one of the main criteria for the suitability of a particular technique for engineering calculations is the possibility of presenting its results in the form of fairly simple analytical or graphical dependencies that can be included in normative reference documents, and from this point of view, methods based on the so-called fuzzy logic have recently begun to spread [15] and other system-wide concepts [16, 17] turn out to be even less suitable. The same applies in most cases to works devoted to the general principles of reducing energy consumption in buildings using various energy-saving solutions, including automatic control of microclimate systems [18–21]. Thus, to date, there are practically no models and solutions that allow us to jointly consider non-stationary processes in rooms serviced by automated microclimate systems, taking into account their physical essence, interconnection and mutual influence and available for use in mass design.

Previously, the author in the works [22–24], a number of issues related to the study of the non-stationary thermal regime of a room serviced by automated microclimate systems were considered, first with proportional [22], and then with integral [23, 24] regulatory laws for various combinations of general exchange and local systems. At the same time, on the basis of a combination of the thermal stability theory and the classical automatic control theory, accurate analytical solutions for the temperature of the internal air with a sudden change in heat supply were obtained, which are quite successfully confirmed by comparison with the results of numerical modeling and some available data from other authors in this field and even allow, under certain conditions, to identify the constructed mathematical model with the determination of the actual parameters of the system. However, with integral control, such solutions were obtained in the form of infinite, albeit rapidly converging series, in addition, the form of their recording did not fully correspond to the traditional nature of the dependencies arising from the implementation of conventional methods of automatic control theory.

Therefore, the actuality of the study under consideration lies in the expediency of further searching for fairly simple, but at the same time having an obvious physical justification for analytical formulas describing the behavior of internal temperature in rooms serviced by local cooling systems equipped with integrated regulators. Such expressions should take into account the most significant factors affecting the processes of heat exchange and heat transfer in fences and room air and equipment of climate systems, including the thermophysical characteristics of building materials, the nature of changes in heat supply and controller parameters. At the same time, they should be presented in a fairly simple form, suitable for use in design practice and more or less consistent with existing solutions known in the theory of automatic control.

Based on the above, the purpose of this work is to obtain a dependence for changing the air temperature in a room equipped with local cooling systems such as split systems regulated by an integral law, which is expressed in elementary functions and is suitable for engineering calculations, with an assessment of its accuracy by comparing with formulas previously discovered by the author and in other sources, taking into account a greater number of factors affecting the non-stationary thermal regime of the room.

Tasks of the work:

- formulation of a system of differential equations that describe transients in a room with a single thermal effect for the case when it is assimilated by an automated split system regulated by an integral law, based on simplifying assumptions that make it possible to apply operational methods to solve;
- obtaining a solution for this system describing the behavior of the indoor air temperature in the specified conditions, recording it in a dimensionless form and analyzing it with various initial data, including in the case of a change in the air capacity of the background general exchange ventilation system;
- assessment of the adequacy and accuracy of the found dependence by comparing it with experimental data for a representative room and the previously achieved results of the author and other researchers.

2. Methods

Similar to the works [22–24], if you enter an excess temperature $\theta_{in} = t_{in} - t_{in.0}$, K, where $t_{in.0}$ denotes the controlled level of the internal air temperature t_{in}, that is, using the terminology for automation systems, the setpoint, in conditions of a sudden change in heat supply and its elimination using a local cooling system (in particular, a split system), which at each moment assimilates the amount of heat Q_c, W, one of the variants of the equation the convective heat balance for the room as a whole will look like this:

$$K_c \theta_{in} + \frac{G_s c_a}{3.6} \frac{\mathrm{d}\theta_{in}}{\mathrm{d}\tau} + M_m c_m \frac{\mathrm{d}^2\theta_{in}}{\mathrm{d}\tau^2} = 0, \tag{1}$$

where Q_{in} is the flow of apparent heat entering the room air due to convection from all sources, W; τ is the period of time, s, that has elapsed after the appearance of a thermal disturbance; G_s is the mass flow rate of the general exchange inflow, kg/h, which can be considered to coincide with the value of the exhaust flow G_{ex}, since the air the balance of the room, unlike the thermal one, is instantaneously stationary with great accuracy; c_a is the specific mass heat capacity of the air equal to 1.005 kJ/(kg·K). In this case, it means that the temperature of the inflow in the studied mode is constant or, in any case, functionally independent of θ_{in} since the general exchange ventilation system does not participate in maintaining θ_{in} but primarily ensures the required cleanliness of the room air. Such a regime is currently becoming widespread, as it makes it possible to reduce the G_s value to the minimum permissible level determined by sanitary and hygienic requirements, and thereby reduce the dimensions of the supply unit and reduce energy consumption for processing supply air in it, as well as simplify the automatic control system.

The parameter K_c in (1) is the equivalent transmission coefficient, W/(K·s), of an automated local system controlled by an integral law for the channel "θ_{in} → derivative of Q_c". The corresponding coupling equation will obviously be written in this way:

$$\frac{\mathrm{d}Q_c}{\mathrm{d}\tau} = -K_c \theta_{in}. \tag{2}$$

At the same time, unlike [22–24], when composing equation (1), the process of propagation of a temperature wave deep into massive enclosing structures over time is not taken into account, but it is assumed that there is some fixed material layer on their inner side facing the room, within which causes the temperature to change to the moment of interest to us. Therefore, the last term (1) includes the product $M_m c_m$, J/K, which makes sense of the total mass heat capacity of this layer, where M_m is its mass, kg; c_m is the specific heat capacity of the corresponding material, J/(kg·K). If the fences are made of different materials, the sum of $\sum M_m c_m$ over all surfaces must be taken into account in (1). The M_m value in this case can be determined based on the area of the structure in question, if you set the thickness of the layer where the temperature wave manages to penetrate. This can be done, for example, using the [22–24] the dependence for the rate of its propagation, moreover, since the thickness of the layer turns out to be proportional to the square root of τ, its effective value for the period under study should be 2/3 of the maximum.

Due to this assumption, (1) turns out to be a linear homogeneous equation of the 2nd order with constant coefficients, as a result of which the usual operational method can be used to solve it. In other words, with the assumptions made, the room under study can be represented from the point of view of the theory of automatic regulation as a linear inertial link of the 2nd order. Then the characteristic equation for (1) will be written as follows:

$$p^2 + \frac{G_s c_a}{3.6 M_m c_m} p + \frac{K_c}{M_m c_m} = 0, \tag{3}$$

where p is the Heaviside operator.

From this, it is not difficult to obtain that, taking into account the obvious initial conditions $\theta_{in} = 0$ and $\frac{\mathrm{d}\theta_{in}}{\mathrm{d}\tau} = \frac{Q_{in}}{M_m c_m}$ at $\tau = 0$, the solution (1) will have the following form:

$$\theta_{in} = C_1 \exp\left(-\frac{\mathrm{Fo}'}{2}\right) \sin\left(\frac{\mathrm{Fo}'}{2} K_G\right), \tag{4}$$

where Fo' is the so-called modified Fourier criterion (dimensionless time) [9], and K_G is a complex parameter (also dimensionless) that determines the properties of the room and its general exchange ventilation system and automated local cooling system. They can be calculated using formulas:

$$\mathrm{Fo}' = \frac{G_s c_a \tau}{3.6 M_m c_m}; \quad K_G = \sqrt{\frac{4 \cdot 3.6^2 K_c M_m c_m}{(G_s c_a)^2} - 1}. \tag{5}$$

It is assumed that the expression under the root in the formula for K_G is non-negative – only in this case an oscillatory component appears in solution (4). However, as it will become clear from the following presentation, with the really possible values of the parameters used, this is exactly the ratio that usually takes place, and for the initial period, there will be no significant difference between the various solutions at all. The dimensional numerical coefficient C_1, K, in expression (4) in this case is defined as follows:

$$C_1 = \frac{2 \cdot 3.6 Q_{in}}{G_s c_a K_G}. \qquad (6)$$

3. Results and Discussion

Fig. 1 shows a comparison of the theoretical dependence for θ_{in} (solid line) according to expression (4) with the results of direct measurements of temperature in a room serviced by an individual split cooling system (dotted line). It should be noted, however, that in fact, its regulation was performed according to the positional principle, but due to the high switching frequency, it still approached the integral one. The thermal disturbance was modeled by turning on a convective electric heater (fan heater) with Q_{in} = 750 W, and the value of $M_m c_m$ was calculated using the actual thermal engineering parameters of building materials in enclosing structures and geometric characteristics of the room [23, 24]. Its area was 14 m^2, the height from floor to ceiling was 3 m, the depth from the outer wall was about 6 m, and then the total surface of the fences facing the room turns out to be about 64 m^2. The average effective density of materials on the inside of the structures was assumed to be p = 600 kg/m^3, and their specific heat capacity c_m = 800 J/(kg·K). Then, if, within the time interval under consideration, we consider the thickness of the layer with a varying temperature equal to 0.01 m, we get $M_m c_m$ = 307200 J/K. The value of G_s was taken into account in the amount of 430 kg/h, and K_i = 2.5 W/(K·s), whence, according to the formula (5) K_G = 14.57. Thus, the root expression in (5) really turns out to be many times higher than 1. Then, the coefficient C_1 in accordance with (6) will be equal to 0.858.

For temperature measurements, a Testo 0560 1110 thermometer with a division price of 0.1 was used, which was installed in the center of the room at a height of 1 m from the floor.

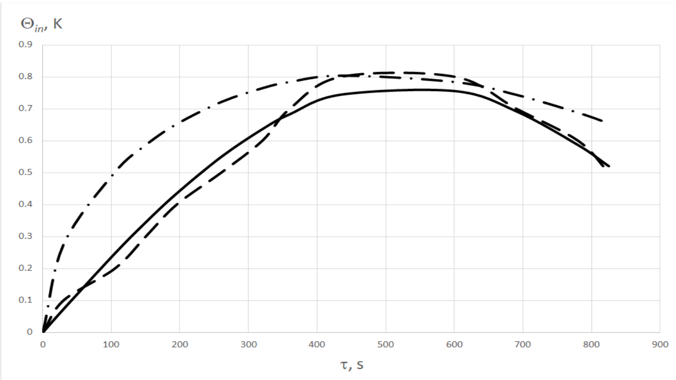

Figure 1. The dependence of θ_{in} on time for a characteristic room in a full-scale experiment (solid line – calculation according to (4), dotted line – experiment, dashed dot – according to the formula (7)).

It can be seen that, practically within the entire studied period from the moment of the occurrence of the heat gain spike, experimental measurements give a dependence character for θ_{in} that differs little from the theoretical one, which confirms the sufficient accuracy and physical validity of the solution option obtained in the proposed work. At the same time, we can talk about the identification of the constructed mathematical model in relation to the selection of the level of parameters $M_m c_m$ and G_s, which ensures the maximum possible coincidence of the calculated and measured curves.

For comparison, the dashed dot in Fig. 1 shows the change in θ_{in} under the same conditions according to the theoretical expression obtained in [23] in the limiting case G_s = 0 and taking into account the nonlinearity of the propagation of the temperature wave in massive fences, which can be written as follows:

$$\theta_{in} = \frac{1.26 Q_{in}}{\sqrt[3]{K_c B^2}} y^{1/3} \left[1 - \frac{y}{3 \cdot 4} + \frac{y^2}{3 \cdot 4 \cdot 6 \cdot 7} - \frac{y^3}{3 \cdot 4 \cdot 6 \cdot 7 \cdot 9 \cdot 10} + \ldots \right], \tag{7}$$

where $1.26 = \sqrt[3]{2},\ y = \frac{4K_c}{B}\tau^{3/2}$ is a dimensionless time parameter, and the value B, W·s$^{1/2}$/K, which determines the intrinsic thermal stability of the enclosing structures of the room, is calculated by the formula:

$$B = \sum \left\lfloor A_m \sqrt{\lambda c \rho} \right\rfloor_i. \tag{8}$$

Here, λ is the thermal conductivity, W/(m·K), of the material of the layer of the i-th massive enclosure facing inside the room, for example, external and internal walls and partitions, as well as floor-to-floor ceilings; A_m is the area of each of the listed fencing structures, m^2. In the example under consideration, the average effective value λ was assumed at the level of 0.45 W/(m·K), if we consider the total surface $\sum A_m$ = 64 m^2, and c_m = 800 J/(kg·K) and p = 600 kg/m^3, as was done above when comparing with experimental data. Then, the value of B will be 29745 W·s$^{1/2}$/K.

Fig. 1 shows that at the initial stage, the room temperature increases faster when calculating according to (7), but this, apparently, can be explained by not taking into account the influence of the room indoor air heat storage capacity when obtaining the solution (7), which is especially significant at low temperatures. However, this circumstance was not taken into account when deriving expression (4), but its structure itself and the corresponding shape of the θ_{in} dependence on time graph, as the results of calculations show, to a certain extent compensates for this disadvantage. At the same time, even despite the noted features, the maximum temperature deviation from the setpoint and the time of its onset, which, generally speaking, are of interest to us primarily when assessing comfort in the serviced area of the room and from the point of view of setting up the automatic control system, within the accuracy of measurements and calculations practically coincide with those obtained by other methods.

Differentiating (4) by time and equating the derivative to zero, we obtain an expression for the criterion Fo' at the time of the maximum deviation of the internal air temperature from the setpoint:

$$\mathrm{Fo}'_{\max} = \frac{2\mathrm{arctg}\left(K_G\right)}{K_G}, \tag{9}$$

from where, substituting the obtained result into the original equation (4), we find the ratio of interest to us first of all for the maximum possible θ_{in}:

$$\theta_{\max} = C_1 \exp\left(-\frac{2\mathrm{arctg}\left(K_G\right)}{K_G} \right) \frac{K_G}{\sqrt{1 + K_G^2}} = C_1 f\left(K_G\right). \tag{10}$$

The graphs of the change in Fo' for the moment of maximum and the function f depending on the magnitude of K_G are shown in Fig. 2 as a solid line and a dotted line, respectively. It can be seen that for K_G > 6, the average value of $f\left(K_G\right)$ = 0.9 can be assumed. Therefore, under the conditions of the considered example, the largest θ_{in} will be equal to 0.858 × 0.9 = 0.77 K, which fully corresponds to the data in Fig. 1.

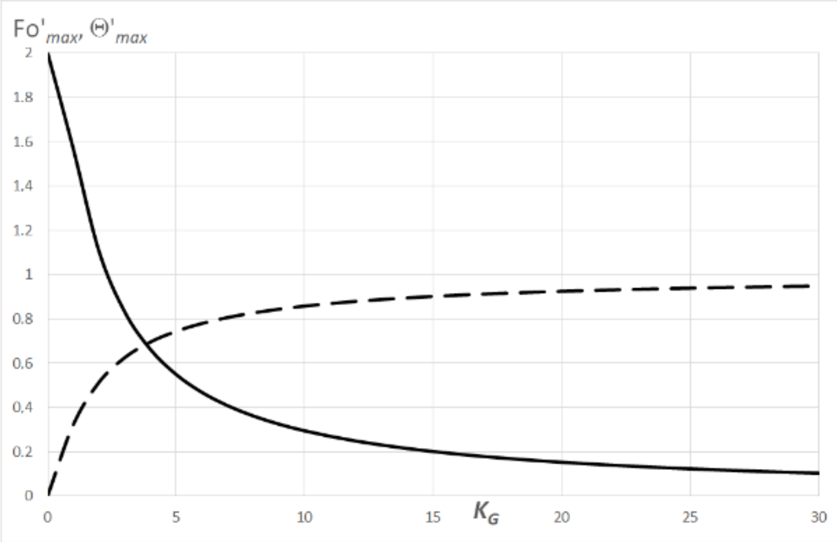

Figure 2. Dependence on the value K_G of the value of the criterion Fo' for the moment of maximum θ_{in} (solid line) and the function $f(K_G)$ according to the formula (10) (dotted line).

Fig. 3 shows, for comparison, the solid line of the already mentioned calculation results according to (4), dots – according to the indications of full-scale measurements [25] in the operating conditions of an air heating system equipped with a similar automation system (after normalization by the value of the largest temperature deviation from the initial level and scaling over time), dotted lines – according to numerical modeling data the operation of an automated water heating system [26], also after appropriate normalization.

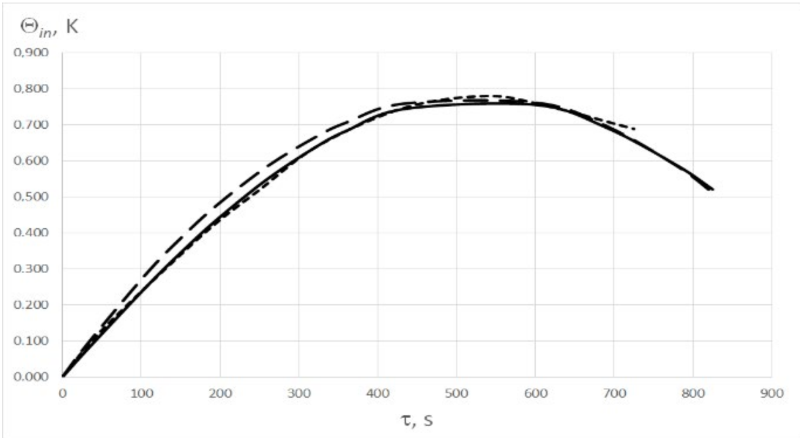

Figure 3. The dependence of θ_{in} on time for a characteristic room (solid line – calculation by (4), dots – experiment [25] with scaling, dotted line – numerical modeling [26] with scaling).

It is acceptable to use such data, since from the point of view of the behavior of excessive temperature, it does not matter whether we are talking about a cooling system that assimilates additional heat gain, or a heating system that compensates for additional heat loss. It can be seen that the discrepancy between the curves practically lies within the error of calculation or measurement, which once again indicates the reliability of the results obtained in this work.

4. Conclusion

- It is proved that the approximate version of the analytical solution obtained in the work, describing the behavior of excessive air temperature in a room serviced by automated equipment such as split systems to ensure an internal microclimate when regulated according to an integral law in the presence of a background inflow with a conditionally constant temperature, with an abrupt change in heat flow, describes the real process of heating or cooling very well in any case, at not too large values of τ.
- It is established that the core of the established dependence for θ_{in} can be explicitly expressed in terms of the product of a sinusoidal and decaying exponential function from a dimensionless complex including the value τ in the first degree, which naturally follows from the assumption

made about the linearity of thermal processes in a room and the properties of solutions of linear homogeneous differential equations of the 2nd order.

- It has been confirmed experimentally on the basis of field measurements in a typical representative room that the mismatch between the actual and calculated temperature values is within the limits of the available error of measuring instruments and the usual accuracy of engineering calculation.
- It is noted that the form of recording the presented solution, containing dimensionless complexes used as independent variables, allows its fairly simple use to identify the constructed mathematical model when comparing it with experimental data, which makes it possible to determine the actual indicators of thermal stability of the room.
- It is shown that the reliability of the results presented in the work is additionally confirmed by their fairly close coincidence in terms of the maximum temperature deviation from the setpoint and the moment of its occurrence with the data of an accurate analytical solution formulated in previous studies in the form of an infinite series [23], which takes into account the nonlinear nature of the propagation of a temperature wave in the material of massive enclosing structures and the actual characteristics of the controller when the absence of background general ventilation.

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