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Calculation of heat resistance of external enclosing structures with heat-conducting inclusions

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Abstract. The paper is devoted to the development of a method for calculating the thermal stability of external enclosing structures with heat-conducting inclusions. Based on the analysis of existing methods and methodologies for solving the problem of heat resistance of enclosing structures with heat-conducting inclusions, the solution of the one-dimensional problem of heat resistance was established to be characteristic for all these works. One of the possible methods for determining the amplitude of temperature fluctuations on the inner surface of the enclosing structure with heat-conducting inclusions is the simulation of non-stationary temperature conditions in software systems. However, this solution causes great difficulties, since it transfers the indicated calculation from engineering to scientific and, therefore, cannot be recommended for direct practical application. The second solution to this problem is to use the convergence coefficient α, which can be obtained empirically. By choosing the value of the coefficient α, one can take into account the effect of a heat-conducting inclusion on the weighted average value of the surface temperature depending on the design of the fence. The paper presents values of the convergence coefficient α for six most common cases of heat-conducting inclusions in enclosing structures. When analyzing the design solutions of external enclosing structures, the features of the influence of heat-conducting inclusions on the averaged amplitude of oscillations on the inner surface were revealed. In the schemes with outer edge or through location of the heat-conducting inclusion, there is a slight influence of the amplitude of the oscillation of the heat-conducting inclusion on the averaged amplitude over the surface of the structure. The greatest degree of influence is exerted by the scheme with the through arrangement of heat-conducting inclusion. On the basis of the comparative analysis, it was found that when constructing harmonics of average temperature fluctuations on the inner surface, preference is given to the methodology with the convergence coefficient.

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1. *Introduction*

Modern outdoor enclosing structures, in most cases, are multilayer systems with a large number of heat-conducting inclusions. In this case, the main attention in the design and calculation of energy indicators is given to the reduced resistance to heat transfer [1–7]. For the theoretical determination of the reduced resistance to heat transfer are developed various methodologies [8–12], which are confirmed and tested in full-scale and laboratory conditions.

This approach to the design of enclosing structures is economically justified from the point of view of saving energy, but do not forget that buildings, first of all, are built for people and comfort conditions should be put at the forefront of the design. Proceeding from the second condition of comfort [13], the regulatory documents put forward restrictions on the change in the amplitude of temperature fluctuations on the inner surface of the external enclosing structures in the summer. This problem was dealt with in detail by A.M. Shklover in the sixties of the twentieth century. Based on his researches many problems were solved related to the thermal stability of enclosing structures and premises. In particular was determined the relationship between the constructive solution of walls and heat resistance [14], but these works and problems were investigated only for multilayer structures without heat-conducting inclusions.

The development of the methodology for calculating thermal stability was continued in their works by Russian scientists [15–18], who proposed various approaches to this problem. Foreign scientists [19–24] dealt with separate problems of the non-stationary regime of the enclosing structures in their works [19–23, 25]. But all these works are characterized by the solution of a one-dimensional problem of heat resistance, which is not correct for modern enclosing structures with numerous heat-conducting inclusions, since for such cases it is necessary to solve problems in a two-dimensional formulation under non-stationary heat transfer conditions. Most of the proposed methods require revision or comparison with the results of field or laboratory studies.

The relevance of the study lies in the fact that the cost of electricity for the air conditioning system in the southern regions of Russia and Ukraine often exceeds the cost for the heating period. This is partly due to the overloading of the air conditioning system, the load for which is calculated according to the methods of calculating the enclosing structures with partial consideration of heat-conducting connections, or, in most cases, ignoring them. The new methodology will make it possible to calculate the thermal stability of enclosing structures with heat-conducting inclusions, which will make it possible to more accurately assess the thermal parameters of structures in the summer period of the year.

The goal of the study is to develop a method for calculating the thermal stability of external enclosing structures with heat-conducting inclusions. To achieve this goal, a number of tasks were set:

- to analyze external enclosing structures and identify the most common structural schemes with heat-conducting inclusions;
- to carry out studies of the distribution of the temperature field inside the enclosing structures with heat-conducting inclusions under non-stationary conditions of heat transfer;
- to determine the numerical values of the convergence coefficients, which make it possible to find the average temperature of the inner surface of the enclosing structure with heat-conducting inclusions.

2. Materials and Methods

The heat resistance of homogeneous multilayer enclosing structures in warm season is normalized by the amplitude indicator of temperature fluctuations on the inner surface and is determined by the ratio of the amplitude A of fluctuations in the outside air temperature to the attenuation coefficient ν in the enclosing structure. The amplitude of fluctuations in the outdoor air depends on two climatic factors: outdoor temperature and solar radiation. Their combined effect on the outer surface of the enclosing structure can be expressed through the effective air temperature at the outer surface of the enclosure T_{con}, K, which is calculated by the equation (1):

$$T_{con} = T_{out} \cdot \sqrt[4]{\frac{G(\alpha)}{G_m(\alpha)}} + r\frac{I(\alpha,\beta)+i(\alpha,\beta)}{\alpha_{out}}, \quad (1)$$

where α and β are, respectively, the angular height and azimuth of the normal to the surface at a given point; T_{out} is outdoor temperature, K; G, I, i are irradiance of the surface at a given point, respectively by thermal, direct solar and scattered solar radiation, W/m^2; G_m is spatial intensity of thermal radiation, W/m^2; r is surface albedo in fractions of a unit; α_{out} is heat transfer coefficient between the outer surface of the fence and the outside air W/(m^2·K).

Thus, the amplitude of the outdoor temperature fluctuation is calculated as the difference between the temperature at 3 o'clock in the afternoon and 3 o'clock in the morning solar time according to the equation (1).

The damping coefficient ν depends on the thermal performance of the layers of the enclosing structure (thermal inertia D and heat assimilation s, W/(m²·K)), and also on the index of heat absorption of the surface Y, W/(m²·K) and is found by the equation (2) [13]:

$$\nu = 0.9e^{\frac{D}{\sqrt{2}}} \frac{(s_1 + \alpha_{out})(s_2 + Y_1)...(s_n + Y_{n-1})(\alpha + Y_n)}{(s_1 + Y_1)(s_2 + Y_2)...(s_n + Y_n)\alpha}. \quad (2)$$

This calculation methodology is valid only for multilayer homogeneous structures, since in the presence of heat-conducting inclusions is observed a change in the temperature field in the thickness of the enclosing structure.

In a homogeneous structure the temperature isotherms are parallel and the heat flux vector is perpendicular to the outer and inner surfaces.

In the presence of a heat-conducting inclusion for the heat flux vectors is observed a change of their directions from the outer surface to the heat-conducting inclusion and, in some cases, heat propagation occurs parallel to the inner surface of the enclosing structure. Thus, when calculating the value of the temperature amplitude's damping of fluctuations in the thickness of the structure, it is not possible to choose the design section along the vector of the heat flux.

One of the possible methods for determining the amplitude of temperature fluctuations on the inner surface of the enclosing structure with heat-conducting inclusions is the simulation of non-stationary temperature conditions in software systems. However, this solution causes great difficulties, since it transfers the indicated calculation from engineering to scientific and, therefore, cannot be recommended for direct practical application.

The second solution to this problem is to use the convergence coefficient α, which can be obtained based on the results of numerical simulation. By choosing the value of the coefficient α, one can take into account the effect of a heat-conducting inclusion on the weighted average value of the surface temperature, depending on the design of the fence, using the relation (3):

$$t_m = \alpha \cdot t_{h.i} + (1-\alpha) \cdot t_h, \quad (3)$$

where t_m is weighted average value of temperature on the inner surface of the enclosing structure with heat-conducting inclusions, K, α is convergence coefficient, $0 \le \alpha \le 1$; $t_{h.i}$ is temperature on the inner surface in the zone of heat-conducting inclusion, K, t_h is homogeneous zone temperature, K.

To determine the coefficient of convergence α, it is necessary to simulate the design scheme of the external enclosing structure with heat-conducting inclusions in an unsteady thermal regime. The measurement results are harmonics of temperature fluctuations $t_{h.i}$ on the inner surface of the enclosing structure at the point of heat-conducting inclusion and temperature t_h of a homogeneous zone, as well as harmonics of the average temperature t_m, calculated using the model. At known temperatures included in equality (3), the convergence coefficient α is found from it.

Thus, computer modeling of the unsteady temperature regime must be carried out for a certain number of typical enclosing structures, for each of them to obtain the values of the convergence coefficient α, and then in subsequent studies, when finding the averaged temperature t_m over the surface, use the ready-made formula (3), substituting only the input data $t_{h.i}$ and t_h.

Computer simulation allows obtaining arrays of temperature values t_m, $t_{h.i}$ and t_h, which are used to plot harmonics. The process of finding the values of α can be based on the approximation of the harmonics of temperature fluctuations by periodic functions, for example, using Fourier series, then Eq. (3) for α is solved analytically and the obtained value of the convergence coefficient is unique for specific specified parameters of the enclosing structure. This approach is applicable even in the case when the initial values of temperatures t_m, $t_{h.i}$ and t_h are small (about 10 values), since this number of points is quite enough for interpolation of a periodic function on one interval of the period length. The estimation of the interpolation error is not performed in this article.

Another way to determine the value of α is iterative, i.e. equation (3) is written in the form (4):

$$t_m^i = \alpha_i \cdot t_{h.i}^i + (1 - \alpha_i) \cdot t_{i_h}, \quad (4)$$

where i = 1, 2, 3,…n, and is solved for each corresponding i-th value t_m, $t_{h.i}$ and t_h. Thus, an array of values α_i is formed, and the convergence coefficient itself is defined as the arithmetic mean over all values of α_{app} (5):

$$\alpha_{app} = \frac{1}{n} \sum_{i=1}^{n} \alpha_i. \quad (5)$$

Then a dependency graph is built (6):

$$t_{m,app}^i = \alpha^{app} \cdot t_{h.i}^i + \left(1 - \alpha^{app}\right) \cdot t_{i_h}, \quad (6)$$

which serves as an approximation of the temperature graph t_m. The article uses an iterative approach, since the number of points in the arrays is 864, which makes it possible to determine the convergence coefficient α with sufficient accuracy.

3. Results and Discussion

Thermally conductive inclusions by their shape and location can be conditionally divided into six types [13]. These types of heat-conducting connections are most typical for residential buildings of low and medium storey (see Fig. 1). For further analysis, we will take foam concrete as the main material of external enclosing structures, and heavy reinforced concrete as heat-conducting inclusions. In this case, the calculations considered several options for each design scheme with a change in the thickness of the enclosing structure from 300 to 500 mm and a density of 500 ... 800 kg/m^3. Let us take climatic conditions for the Donetsk city as the calculated parameters of the summer period.

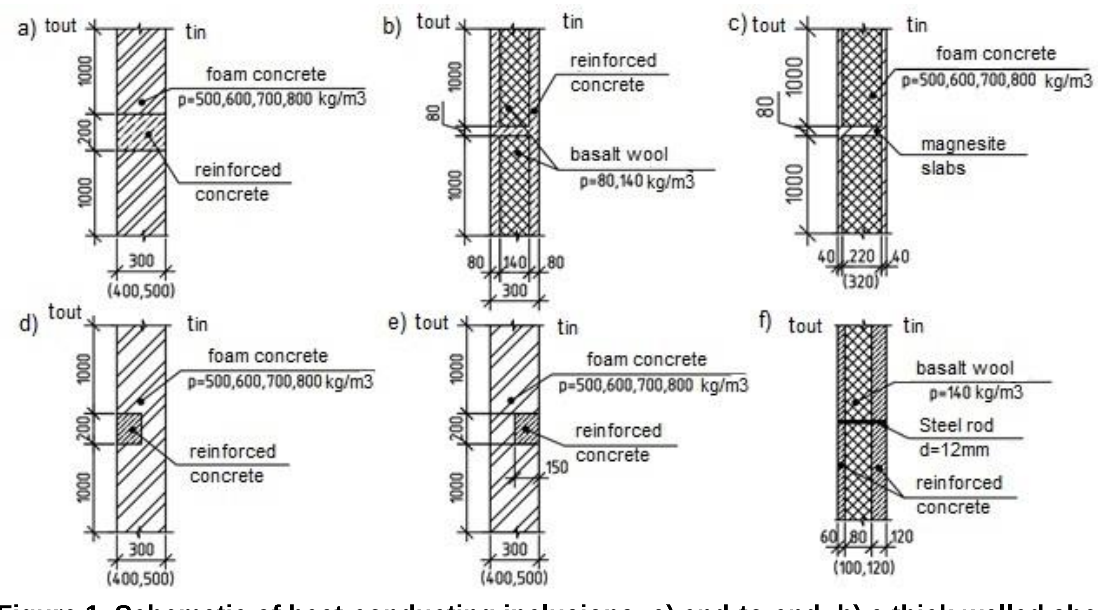

Figure 1. Schematic of heat-conducting inclusions: a) end-to-end; b) a thick-walled shell; c) a thin-walled shell; d) at the inner edge; e) at the outer edge; f) steel through the bar.

In the ELCUT6.4 software package the non-stationary temperature regime was simulated for an external wall scheme with a through heat-conducting connection (Fig. 1a). As the analysis result of changes in the temperature field of a homogeneous zone in time was found the effect of "buffering" of heat. Let us consider in more detail the distribution of the temperature flow in time for this case (Fig. 2). The cycle of temperature fluctuations inside the enclosing structure is divided into several stages, depending on the effect of outdoor air and solar radiation. The countdown of the first stage starts from reaching the maximum temperature in the thickness of the building envelope (Fig. 2a). The next stage begins with the beginning of cooling of the outer surface, while is noted the continuation of penetration and maintenance of the maximum temperature in the structure (Fig. 2b).

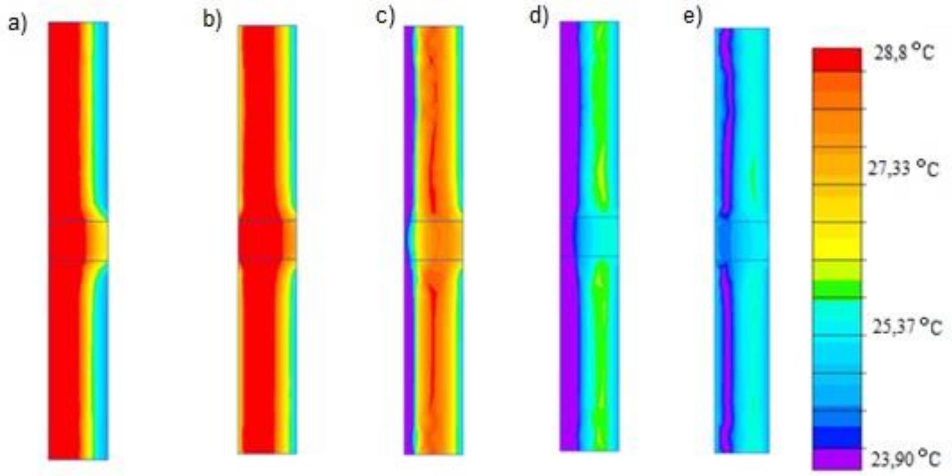

Figure 2. Distribution of the temperature field in the thickness of the enclosing structure during the period: a) the initial phase of heating; b) maximum temperatures; c) the beginning of cooling; d) minimum temperature; e) final cooling phase.

In the third stage, there is a simultaneous cooling on the outer surface and a decrease in the zone of maximum temperatures due to the transfer of heat to colder zones (Fig. 2c), while heat spreading is observed both towards the interior of the room and towards the outer zone of the wall. The fourth stage is characterized by the spread of the minimum temperature deep into the structure (Fig. 2d), however, the zone with an increased temperature in the thickness of the wall prevents the penetration of low temperatures and partially continues to heat the inner zone of the wall. At the fifth stage, the outer surface begins to warm up (Fig. 2e). However, a zone with low temperatures is formed near the outer surface, which later, when the structure warms up, is similar in its behavior to the zone of maximum temperatures from the third stage with a difference in temperatures: the third stage did not "pass" low temperatures, and the fifth – increased ones. When considering the temperature distribution in the zone of heat-conducting inclusion (Fig. 2), the phenomenon of "buffering" of heat is not observed. The temperature change in the thickness of the heat-conducting inclusion is described by the harmonic (curve 2, Fig. 3), similar to the harmonic of the temperature change on the outer surface (curve No. 1, Fig. 4), proportional to the damping coefficient.

When comparing the harmonics of temperature fluctuations on the inner surface in the zone of the heat-conducting inclusion and the homogeneous zone (curves 2 and 3, Fig. 3) were found large differences in amplitudes (in 3 times) and insignificant period shifts for circuit a) Fig. 1. When analyzing the harmonics on the inner surface of the homogeneous zone and the weighted average temperature on the inner surface (curves 1 and 3, Fig. 4), obtained in the ELCUT6.4 software package were found insignificant deviations of the amplitude and period. Thus, it becomes possible to obtain temperatures on the inner surface using the proposed methodology through the coefficient α.

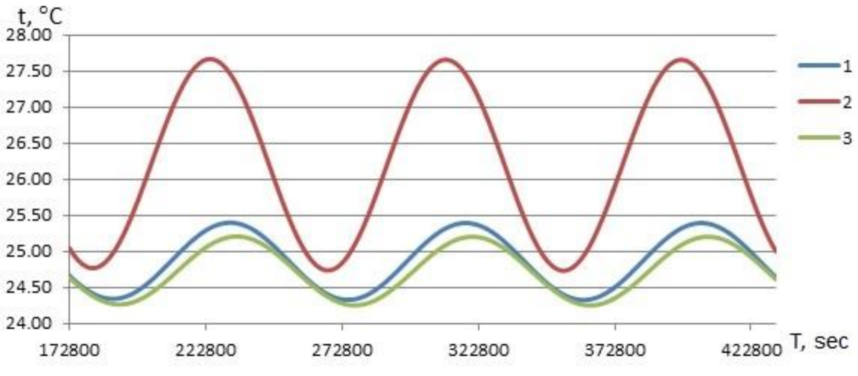

Figure 3. Harmonics of the amplitudes of temperature fluctuations on the inner surface in the place: 1 – averaged over the surface; 2 – heat-conducting inclusion; 3 – homogeneous surface.

For scheme a) Fig. 1 were calculated the coefficients α, which, depending on the density and thickness of the material, are given in Table 1. When comparing the values of the coefficient α with the resistance to heat transfer, thermal inertia, and the coefficient of heat assimilation, no were found simple dependencies with a high degree of convergence.

Table 1. Convergence coefficient α values for the scheme a) Fig. 1

Thickness, mm	Density, kg/m^3			
	500	600	700	800
300	0.1911	0.0884	0.0998	0.0935
400	0.0597	0.1231	0.1640	0.1338
500	0.0696	0.1230	0.1563	0.1049

Analysis of the amplitudes of fluctuations in the external temperature (curve 2, Fig. 4) and on the inner surface shows that for this scheme, the vibration amplitude for a heat-conducting inclusion decreases from 13 to 40 times for the averaged surface.

In [13, 25] are presented the calculations for reducing the amplitude of temperature fluctuations on inner surface of the enclosing structure in summer through the damping coefficient, but is not considered the movement of heat from the inner zone to the outer surface. Due to this, the values of V.N. Bogoslovskii more by 40 % from those obtained as the result of numerical simulation of the circuit e) (Fig. 1).

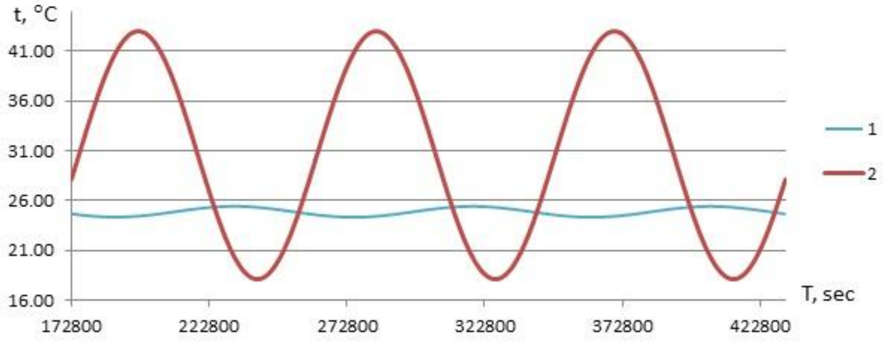

Figure 4. Harmonics of averaged amplitudes of temperature fluctuations: 1 – on the outer surface; 2 – on the inner surface.

As a result of modeling scheme b) (Fig. 1), convergence coefficients α were obtained equal to 0.1911 and ≈ 0.000 for insulation thicknesses of 80 mm and 140 mm, respectively. The convergence coefficient for thickness of 140 mm is close to zero, but nonzero, since the harmonics of temperature fluctuations on the inner surface in a homogeneous zone and averaged over the surface practically coincide (curves 1 and 3, Fig. 5). At the place of the heat-conducting inclusion, although a large amplitude of oscillations is observed (curve 2, Fig. 5), due to the small thickness of the heat-conducting inclusion, it does not affect the average value of the amplitude over the entire inner surface of the enclosing structure.

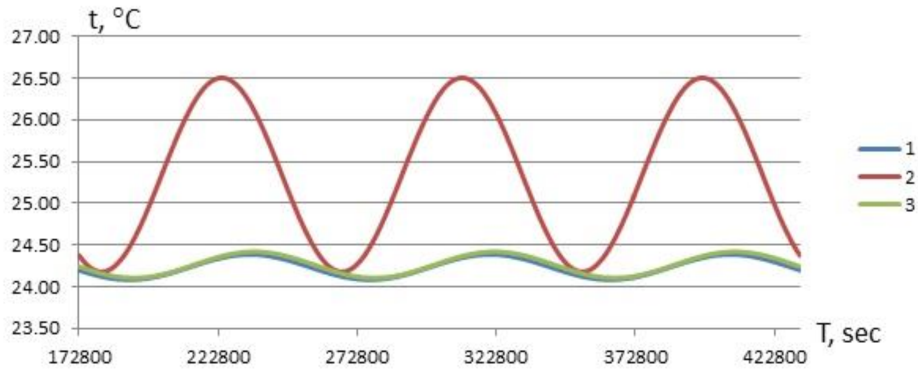

Figure 5. Harmonics of the amplitudes of temperature fluctuations on the inner surface in the place: 1 – averaged over the surface; 2 – heat-conducting inclusion; 3 – homogeneous surface.

When analyzing the results of modeling the structure with a heat-conducting connection according to scheme c) (Fig. 1) were found the convergence factors α (Table 2). It was also found that due to the small proportion of heat-conducting inclusion, there is a slight difference in the amplitudes of oscillations (Fig. 6) on the inner surface. In this case, the heat-conducting inclusion can be neglected.

Table 2. Convergence coefficient α values for the scheme c) Fig. 1

Thickness, mm	Density, kg/m³			
	500	600	700	800
300	0.4902	0.1663	0.2696	0.4174
400	0.0195	0.0195	0.6818	0.0906

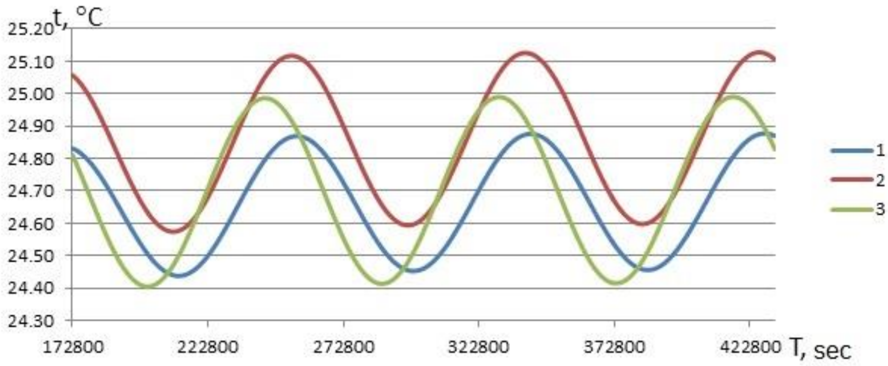

Figure 6. Harmonics of the amplitudes of temperature fluctuations on the inner surface in the place: 1 – averaged over the surface; 2 – heat-conducting inclusion; 3 – homogeneous surface.

The simulation results of circuit d) (Fig. 1) are similar to the simulation results of circuit a), but with a structure thickness of 500 mm, it was found that the heat-conducting connection has practically no effect on the averaged amplitude of temperature fluctuations on the inner surface. Table 3 shows the values of the convergence coefficient α.

Table 3. Convergence coefficient α values for the scheme d) Fig. 1

Thickness, mm	Density, kg/m³			
	500	600	700	800
300	0.1964	0.2517	0.1601	0.1787
400	0.1559	0.0718	0.2801	0.0010

With an external blind arrangement of a heat-conducting inclusion, as in diagram e) (Fig. 1), a change in the amplitude of oscillations was recorded only at a thickness of 300 mm, at large values of the thickness, the harmonic of the temperature of the homogeneous zone is close to the average (Fig. 7). The obtained convergence coefficients α for a thickness of 300 mm are presented in Table 4.

Table 4. Convergence coefficient α values for the scheme e) Fig. 1

Thickness, mm	Density, kg/m³			
	500	600	700	800
300	0.0493	0.0862	0.0141	0.0890

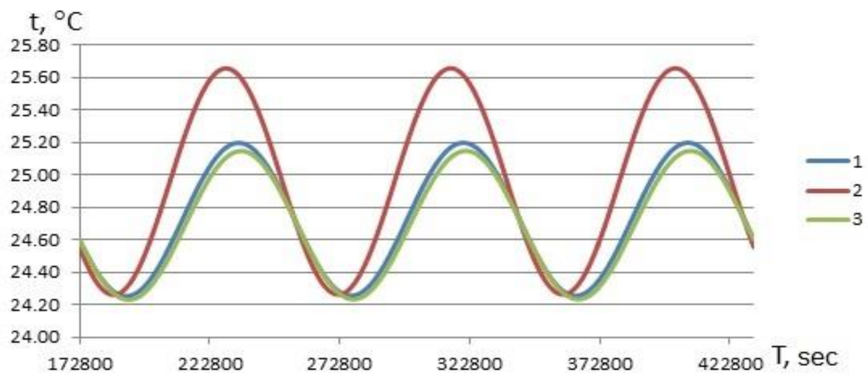

Figure 7. Harmonics of the amplitudes of temperature fluctuations on the inner surface in the place: 1 – averaged over the surface; 2 – heat-conducting inclusion; 3 – homogeneous surface.

The cardinal difference is the scheme f) (Fig. 1) with a through heat-conducting connection: even with a small diameter of a steel rod (∅12 mm) it causes significant disturbances in the amplitude of temperature fluctuations on the inner surface. With an amplitude in the homogeneous zone 0.46 °K and 5.94 °K for heat-conducting inclusion (Fig. 8), the average amplitude over the surface is 3.44 °K, i.e, the degree of influence of the heat-conducting inclusion is 12.91. For the previous schemes this value ranges from 3.0 to 5.0. Also, the values of the convergence coefficient were calculated for various thicknesses of the enclosing structure, which were: α = 0.4451 for 80 mm; α = 0.7040 for 100 mm and 120 mm.

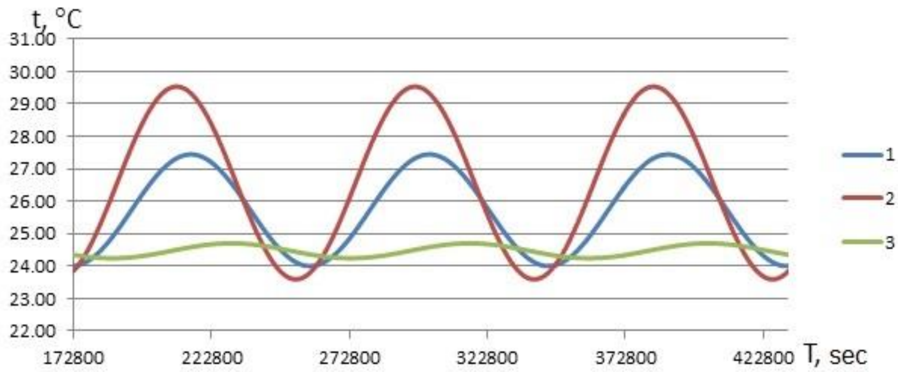

Figure 8. Harmonics of the amplitudes of temperature fluctuations on the inner surface in the place: 1 – averaged over the surface; 2 – heat-conducting inclusion; 3 – homogeneous surface.

4. Conclusions

The revealed "buffering" effect of the heat flow in the thickness of the enclosing structure will allow, when designing, to reduce the amplitude of oscillations on the inner surface by 2 ... 3 K due to the selection of the optimal density and heat resistance of materials. Additionally, it is necessary to study this effect in the winter period of the year and its degree of influence on the temperature of the inner surface of the enclosing structure during the period of daily fluctuations of the outer air or uneven operation of the heating system.

When analyzing the design solutions of external enclosing structures were revealed the features of the influence of heat-conducting inclusions on the averaged vibration amplitude on the inner surface. In circuits with the location of the heat-conducting inclusion at the outer edge or through, there is a slight influence of the amplitude of the vibration of the heat-conducting inclusion on the averaged amplitude over the structure surface. In structures in which a heat-conducting inclusion plays the role of a shell or is located at the outer edge, the degree of influence is insignificant, and at maximum thicknesses is absent. The greatest degree of influence is exerted by a scheme with a through arrangement of a heat-conducting inclusion in the form of a steel rod ∅12 mm. This heat-conducting inclusion has a 4 times greater effect on the amplitude of fluctuations in the temperature of the inner surface than in circuits with a through heat-conducting inclusion in the form of a 200 mm thick concrete lintel. Based on this diagram, it can be concluded that structures with a high percentage of reinforcement or the presence of transverse reinforcement will not meet design standards in the summer season.

As a result of a comparison of the two methods for constructing harmonics of average temperature fluctuations on the inner surface (Fig. 9), preference is given to the method with a convergence coefficient.

This methodology showed the convergence of the obtained harmonic from the theoretical one to 95 %. The mean square method showed high convergence in the average temperature zone of the curve, but in the peak part of the harmonics, this method reduces the maximum and minimum temperatures. This underestimation of temperature values sharply reduces the normalized coefficient – the amplitude of oscillations on the inner surface, thus the calculated values of the average amplitude of the surface are significantly reduced relative to the data obtained as a result of modeling the unsteady heat flow in the ELCUT 6.4 software package.

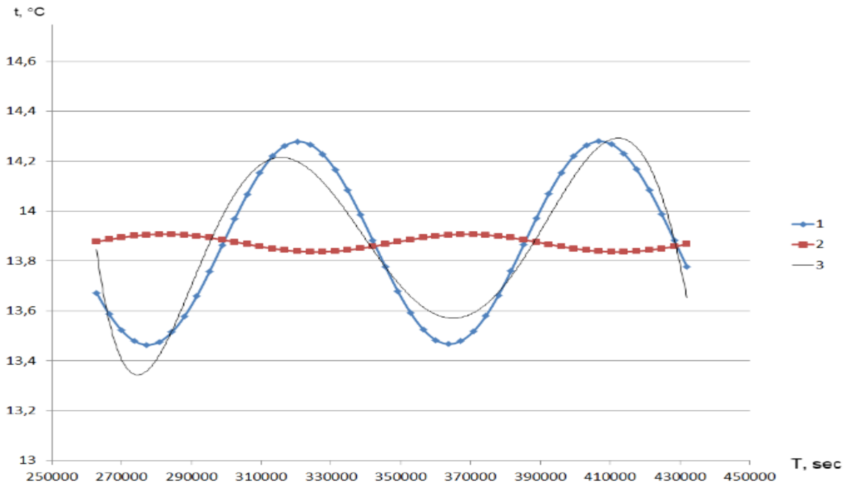

Figure 9. The fragment of the harmonic of temperature fluctuations on the inner surface obtained: 1 – using the convergence factor; 2 – least squares method; 3 – as a result of numerical simulation.

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