FIRE AND INDUSTRIAL SAFETY (CIVIL ENGINEERING)

UDC 624.042.5:536.468: 614.841.3

Voronezh State University of Architecture and Civil Engineering
Ph. D. in Engineering, Assoc. Prof. of Dept. of Fire and Industrial Safety A. M. Zaytsev
D. Sc. in Engineering, Prof. of Dept. of Fire and Industrial Safety V. L. Khudikovsky
Russia, Voronezh, tel.: (473)236-93-50

Military Voronezh Engineering University (Voronezh)
D. Sc. in Engineering, Prof. of Dept. of 72 Aviation Engines S. P. Aksenov
Russia, Voronezh, tel.: (473)226-38-05; e-mail: vestnik_vgasu@mail.ru

A. M. Zaytsev, V. L. Khudikovsky, S. P. Aksenov

MODIFICATION OF DIMENSIONALITIES OF COEFFICIENTS OF HEAT CONDUCTION, TEMPERATURE CONDUCTION AND DERIVATION OF FOURIER'S EQUATION OF UNSTEADY HEAT CONDUCTION

Problem statement. A study of building structure heating in case of fire requires solutions of the problems of multilayer structure heating. Available analytical solutions of such problems are cumbersome mathematical formulae which are of little use for engineering practice.
Results. New dimensionality of heat and temperature conduction coefficients is established by the author of the paper on the basis of modern concepts of heat transfer in solids. This dimensionality reflects physical sense of the coefficients and enables the author to derive modified Fourier's equation of unsteady heat conduction. New technique for the calculation of multilayer structures heating was developed based on the obtained equation. The technique involves reduction of multilayer structures to single-layer wall.
Conclusions. High accuracy and efficiency of the method proposed are shown by the example of calculation of heating of two-layer wall reduced to single-layer wall by the comparison with numerical methods and analytical calculations for single-layer wall.

Keywords: heat conduction coefficient, temperature conduction coefficient, modified Fourier's equation of unsteady heat conduction, heating, multilayer building structures.

Introduction

Starting from the 20^{th} century, there has been an intense development of analytical methods for unsteady heating of solid bodies, as well as of multi-layer building constructions. By now, analytical solutions have been obtained for the calculation of unsteady heating of various constructions which are widely used in engineering practice.

Nevertheless, the analysis by means of various mathematical physics methods performed on heating solutions for multi-layer constructions and of building constructions as well under the action of a high temperature of fire under various boundary conditions shows [1—8] that ultimately, calculating expressions for them invariably turned out to be elaborate formulas. For these to be used in practice, a further study is needed which hinders the calculation process. The exception is numerical methods using computing technology.

1. Current interpretation of the dimensionality of the coefficient of heat conductivity

The equation for unsteady heat conduction was proposed by J. B. Fourier in 1725. The dimension of the coefficient of heat conductivity was the same as for steady heat conduction, which does not comply with the physical essence of the processes of unsteady heat conduction. This error is of theoretical, methodical and practical importance. To eliminate it, let us first consider a one-dimensional steady temperature field (Fig. 1) [1, 9, 10].

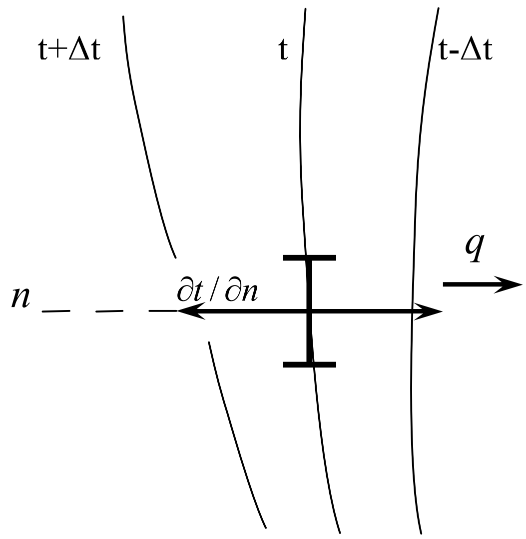

Fig. 1. Isotherms of a steady temperature field

A temperature field in steady processes is determined by the equation

$$t = t(x). \qquad (1)$$

The sharpest change in temperature occurs in the direction to the normal n to an isothermal plane. The limit of the ratio of the temperature change Δt to the distance between the isotherms on the normal Δn is called the temperature gradient [1] and designated by one of the following symbols:

$$lim\left(\Delta t / \Delta n\right)_{\Delta n \to 0} = \frac{\partial t}{\partial n} = qrad\, t. \tag{2}$$

Temperature gradient is a vector directed towards a normal to the isothermal plane towards the increase in temperature. Its dimensionality is ^{0}C/m. Heat passing through in a unit of time and related to a unit of area of an isothermal plane is called the density of a heat flow.

The major heat conduction law shows that density of a heat flow is directly proportional to the temperature difference and is determined by the equation

$$q = -\lambda grad\ t\ \ or\ \ x > -\lambda \frac{\partial t}{\partial x}. \tag{3}$$

The physical sense of the conductivity coefficient is determined from the ratio (4) for a steady temperature field, which means that

$$\frac{Q}{S\tau} = -\lambda \frac{T_2 - T_1}{x_2 - x_1}. \tag{4}$$

The conductivity coefficient thus equals the heat conducted in a unit of time through an area unit as temperature varies in a unit of length of a normal which is one degree and thus has dimensionality kJ/m · h · ^{0}C.

2. The deduction of a modified equation for unsteady heat conduction by Fourier

Heat transmitted in steady heat conduction and passing through two surfaces located at some distance away from each other will be the equal, but in unsteady heat conduction some of the heat is used to heat (cool) the body, therefore heat passing through these surfaces will be different.

The deduction of a differential equation for unsteady heat conduction for a one-dimensional temperature field is given in, for instance, [1, 9]. For this purpose, in one-dimensional and isotropic, non-restricted plate an elementary parallelepiped evolves whose volume is *dx dy dz* (Fig. 2).

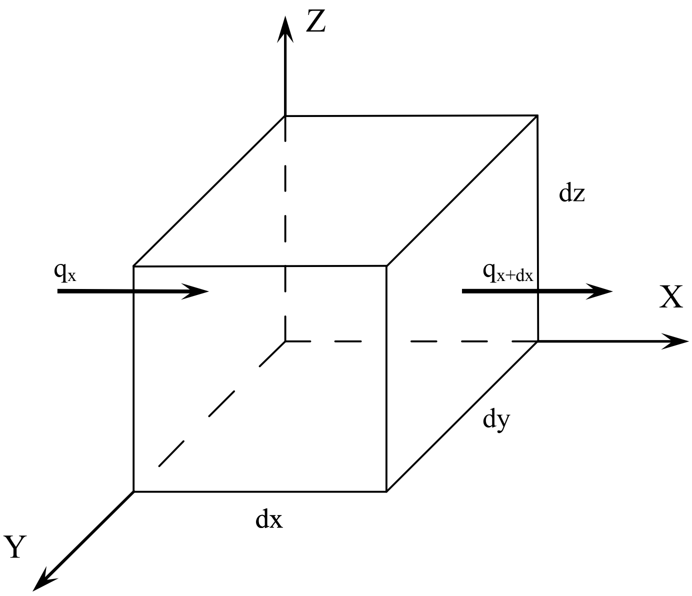

Fig. 2. Heat flowing through the elementary volume of the body in the unsteady mode

Heat passing through the left side *dy dz* into the parallelepiped in a unit of time is $q_x\, dy\, dz$, while heat passing into the opposite side in a unit of time is $q_{x+dx}\, dy\, dz$. If $q_x > q_{x+dx}$, the elementary parallelepiped heats up, the difference between these flows according to the energy conservation law then equals the heat accumulated, i. e.

$$q_x\, dy\, dz - q_{x+dx}\, dy\, dz = c\rho \frac{\partial t}{\partial \tau} dx\, dy\, dz, \tag{5}$$

where c is the coefficient of specific heat capacity of the body; ρ is the density of the body.

The value q_{x+dx} is an unknown function x. If we arrange it in the Taylor's series and restrict ourselves to the first two members of the series, we can write

$$q_{x+dx} \approx q_x + \frac{\partial q_x}{\partial x} dx. \tag{6}$$

Then, from equation (5) we have

$$-\frac{\partial q_x}{\partial x} dx\, dy\, dz = c\rho \frac{\partial t}{\partial \tau} dx\, dy\, dz. \tag{7}$$

Using the equation for a heat flow (3), we get Fourier's unsteady heat conduction equation,

$$\frac{\partial t}{\partial \tau} = a \frac{\partial^2 t}{\partial x^2}, \tag{8}$$

where t is the temperature of the body, degrees; x is the coordinate of the body, m; a is the heat conduction coefficient, m^2/h.

The above deduction of a differential equation for Fourier's unsteady heat conduction illustrates the formal approach to the use of dimensionality of heat conduction coefficient obtained for the conditions of unsteady heat conduction.

A fault of this approach is seen, for instance, from Fig. 2, as well as from the formula (6), which means that a different amount of heat is transmitted through the opposite sides of the parallelepiped. Some of the heat remains in the parallelepiped, due to which fact its temperature increases. As noted in [11], "as the terminology was crucially reviewed, there was a constant need as new terms emerged to leave some of the terms intact, which, if strictly evaluated, are not quite satisfactory but do not cause confusion and practical errors (for instance, "heat conduction coefficient")".

In the light of the modern conceptions of the heat conduction process (for example, in [12]), heat in solid bodies is transmitted by the motion of electrons and oscillation process in a crystal lattice of the body. Thus, heat conduction in solid bodies is intimately associated with the volume of the body, therefore the dimensionality of the heat conduction coefficient has to be defined in the corresponding manner, i. e. as the amount of heat transmitted in a unit of volume as the temperatures of the opposite surfaces (a one-dimensional field) differ in one degree. This is clearly seen in Fig.2. Therefore, the dimensionality of the heat conduction coefficient is defined as an amount of heat passing through a unit of volume in a unit of time with the difference of the temperatures on the opposite surfaces in one degree and has the dimensionality of $kJ/m^3 \cdot h \cdot {}^0C$.

We have thus clarified the physical essence and adequate dimensionality of the heat conduction coefficient for unsteady heat conduction. So, the dimensionality of the thermal conduction coefficient is as follows:

$$a = \frac{\lambda}{c\rho} = \frac{kJ}{m^3 \cdot h \cdot degrees} \cdot \frac{kg \cdot degree}{kJ} \cdot \frac{m^3}{kg} = \frac{1}{\tau} = \tau^{-1}. \qquad (9)$$

The coefficient a thus has the dimensionality τ^{-1} and has the physical sense of the coefficient of the relaxation of the temperature inequalities in the solid body or, as noted in [4], characterizes the speed of the temperature change in the solid body in unsteady heat conduction.

Having obtained a new dimensionality of the coefficient *a*, we get an inconsistency between the dimensionalities in the left and right parts of the equation for Fourier's unsteady heat conduction, i. e.

$$\frac{degrees}{h} \neq \frac{degrees}{h \cdot m^3}. \tag{10}$$

To eliminate this inconsistency, it is enough to move to dimensionless coefficients. A specified size of the body which is expressed in, for instance, meters, will be expressed in the dimensionless form in relation to 1 m.

Thus, instead of, for instance, $x = 0.3$ m, we get

$$X = \frac{x}{1} = \frac{0,3m}{1m} = 0,3. \tag{11}$$

As a result, we get the following Fourier's modified unsteady heat conduction equation

$$\frac{\partial t}{\partial \tau} = a\frac{\partial^2 t}{\partial X^2}, \tag{12}$$

where X is a dimensionless coordinate; a is a relaxation coefficient of the temperature inequalities of the solid body with the dimensionality h^{-1}.

Now, the dimensionalities in the right and left parts of the equation (12) are identical and equal ^0C /h. The obtained modified equation is not different from Fourier's unsteady heat conduction equation, as the right and left parts of the equations (8) and (12) are identical. However, for the obtained equation, the value of Fourier's criterion is significantly more simple, for it has only two arguments *a,* and *τ* which have dimensionality. More importantly, the modified equation allows one to solve the problem of heating multi-layer constructions by transforming them into a single-layer wall.

3. Methods of moving from the task of heating multi-layer systems to heating of a single-layer wall

The modified Fourier's equation for unsteady heat conduction yields a simple solution for heating multi-layer constructions due to transforming them into a single-layer construction. Let us analyze this using the example of the solution of the problem of the first order when a certain temperature is specified on a surface of the system. Let us accept that it is a constant value $t_{пов}$ = const and that there is no heat exchange on the opposite side.

The mathematical problem in this case reduces to solving a system of differential equations

$$\begin{cases} \dfrac{\partial t_1(X_1,\tau)}{\partial \tau} = a_1 \dfrac{\partial^2 (X_1,\tau)}{\partial X^2}, \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \dfrac{\partial t_n(X_n,\tau)}{\partial \tau} = a_n \dfrac{\partial^2 (X_n,\tau)}{\partial X_n{}^2} \end{cases} \tag{13}$$

with the following initial and boundary conditions:

$$\begin{cases} t_1(X_1,\tau) = \ldots = t_n\ (X_n,\tau) = t_0, \\ t_i(\delta_i,\tau) = \ldots = t_{i+1}\ (\delta_{i+1},\tau), \\ \lambda_i \dfrac{\partial t_i(\delta_i,\tau)}{\partial X} = \lambda_{i+1} \dfrac{\partial t_{i+1}(\delta_{i+1},\tau)}{\partial X}, \\ t_1(0,\tau) = t_{\text{const}};\ \lambda_n \dfrac{\partial t_n(\delta_{общ},\tau)}{\partial X} = 0, \end{cases} \tag{14}$$

where $t_i(X,\tau)$ is the temperature of *i*-th plate; X is a dimensionless coordinate; δ_i is a relative dimensionless coordinate; τ is the time; λ_i, a_i are coefficients of heat conduction and the speed of the substance temperature change in the *i*-th layer; t_0 is the initial temperature of the system of plates; t_{const} is a constant temperature on the surface of the first plate.

In order to make the solution of this problem easier, we transform a multi-layer plate into a single-layer one with a certain value of the coefficient *a*. If we regard the coefficient *a* as a collection of three values $a = \lambda/c\rho$, the ratio λ/ρ included in it (according to the accepted dimensionality of the heat conduction coefficient λ) will get the dimensionality

$$\frac{\lambda}{\rho} = \frac{kJ}{m^3 \cdot h \cdot {}^0C} \cdot \frac{m^3}{kg} = \frac{kJ}{kg \cdot h \cdot {}^0C}. \tag{15}$$

This ratio shows what amount of heat 1 kg of the substance needs for its temperature to go up by 1 ^{0}C in 1 hour. This part of the coefficient *a* is time-dependent.

Another component of the coefficient *a*, specific heat coefficient, has the dimensionality kJ/kg · ^{0}C. This value is not time-dependent. The product of specific heat coefficient per a body volume is a specific volume heat of the body (i. e. (cV) or ($c\delta^3$), where V is the volume of the body; δ is the thickness of the plate) and describes the connection between the amount of heat (kJ) and the temperature of a body of unit density. The specific volume heat shows what amount of heat is needed to be supplied to a unit if the body volume so that its temperature went up to 1 ^{0}C.

It should be taken into account that it is temperatures of the body volumes but not their exterior energies that level off in unsteady heat conduction [13]. Specific heat and density of the body (therefore, the mass as well) are different indicators: specific heat describes the temperature and density characterizes the interior energy of the body. Therefore, in order to move from a multi-layer to a single-layer plate in unsteady heat conduction, it is necessary that all of the layers are made homogenous according to the value of the specific volume heat of the substance so that the following condition is true for all the layers transformed

$$c_i \delta_i^3 = c_{\max} \left(\delta_i\right)_м^3, \tag{16}$$

where $c_{\max}$ is accepted for a layer with the value $a_{\max}$.

We thus have arranged the temperature scales of some layers. Therefore the thicknesses of the modified layers can be determined by the formula

$$\delta_{i,м} = \delta_i \sqrt[3]{\frac{c_i}{c_{\max}}}. \tag{17}$$

In order to preserve the thermal resistance of the initial and modified i-th layer, the following should be fulfilled

$$\lambda_{i,\,м} = \lambda_i \frac{(\delta_i)_m}{\delta_i}. \tag{18}$$

In order to preserve the condition of energy conservation for the initial and modified thickness of the i-th plate, the inequality should be valid

$$c_i \cdot \delta_i^3 \cdot \rho_i \cdot \Delta t_i = c_{\max} \cdot \left(\delta_i^3\right)_m \rho_{i,\,\mathrm{m}} \cdot \Delta t_i, \tag{19}$$

from which the value of the density coefficient for a modified layer can be determined.

As a result of the transformations, we got a modified single-layer plate with the identical values of specific volume heat of some layers which correspond to the value for the i-th layer with the values a_i which equals $a_{\max}$. Based on that, we have transformed the thicknesses of the other plates. The overall thickness of the obtained single-layer plate is thus

$$R_{м} = \sum_{i=1}^{n} X_i = X_1 + \sum_{i=2}^{n} X_{i,m}. \tag{20}$$

We thus have a single-layer plate with the overall thickness determined by the formula (20), with identical values of specific volume heat for all the layers which is $c_{\max} \cdot \delta^3_{\max}$. The values $\delta_{i,м}$, $\lambda_{i,м}$ and $\rho_{i,м}$ are calculated by the formulas (17), (18), (19) respectively.

The unsteady temperature field in each point of the obtained single-layer plate is determined by the relative coordinate and Fourier's criterion. For the obtained single-layer plate, a unique value of the coefficient a_i, (that equals $a_{\max}$) is accepted. The value of Fourier's criterion for the i-th layer of the modified single-layer plate, due to a change in the coefficient a, is to be determined by the formula

$$F_{0,i} = K_{i,\tau} a_{\max} \tau_i / R_{np}^2, \tag{21}$$

where $a_{\max}$ is the overall identical value for all the layers of the modified single-layer plate, R_{np} is a reduced overall thickness of the modified single-layer plate which is calculated by the formula (20); the coefficient $K_{i,\tau}$ is introduced to preserve homochronity [14] (time similarity) of heating of all the layers of the initial multi-layer plate due to a change in the coefficient a.

Therefore, for a layer with the value a_i, that equals $a_{\min}$, the value of the product $a\tau$ is ($a_{\max}/a_{\min}$) times increased. Thus, for the other layers, time is to be increased by the same number of times. Thus the coefficient $K_{i,\tau}$ for the other layers is defined to be

$$K_{i,\tau} = a_{\max} / a_i. \tag{22}$$

In order to preserve the similarity (homochronity) in the course of heating all the layers of the multi-layer plate, it is necessary that the value a_i is also increased by the same coefficient for all the layers, i. e. Fourier's criterion remains equal for each initial layer. Thus, during calculations, the coefficient a_i for heating of the i-th layer is to be $K_{i,\tau}$ times increased.

So, in order to calculate heating of the other layers of the initial multi-layer plate, a nomogram for the calculation of heating of a single-layer plate can be used. For each initial layer, it is necessary that there is its own value of Fourier's criterion for each initial layer according to the formula (21).

The scheme of moving from the multi-layer plate with various thermophysical characteristics to the single-layer plate homogenized according to the value $c_{\max} \cdot \delta^3_{\max}$ is presented in Fig. 3. A change in the coefficient a is compensated by the coefficient $K_{i,\tau}$ (from the conditions of preserving homochronity of the process for the entire system).

a)

a_1	...	a_i	...	a_n
δ_1	...	δ_i	...	δ_n
c_1	...	c_i	...	c_n
λ_1	...	λ_i	...	λ_n
ρ_1	...	ρ_i	...	ρ_n

b)

$K_{i,\tau}(a_i)_{max}$	...	$K_{i,\tau}(a_i)_{max}$	...	$1(a_i)_{max}$
(δ_1)	...	$(\delta_i)_M$	...	$(\delta_n)_M$
$(c_i)_{max}$	...	$(c_i)_{max}$	...	$(c_i)_{max}$
(λ_1)	...	$(\lambda_i)_M$	...	$(\lambda_n)_M$
(ρ_1)	...	$(\rho_i)_M$	...	$(\rho_n)_M$

Fig. 3. Scheme of transforming the multi-layer plate into the single-layer plate:
a) parameters of the multi-layer plate;
b) parameters of the specified single-layer plate homogenized according to the value $c_{\max} \cdot \delta^3_{\max}$

For the sake of definiteness, the coefficient a acquires the minimal value for the n-th layer the maximum value for the first layer, the intermediate value for the i-th layer. Therefore, the coefficient $K_{i,\tau}$ for the n-th layer equals 1, for the other layers it equals the value calculated according to the formula (22).

4. Methods of calculating the heating of multi-layer constructions based on their transformation into a single-layer plate

The calculation of the heating of a multi-layer plate transformed into the single-layer plate is made in the following order:

1. All the layers of the multi-layer plate are homogenized according to the value $c_{\max} \cdot \delta^3_{\max}$, the thickness of the modified layers is calculated by the formula (17).
2. The overall thickness of the modified layer as well as the relative coordinates of the i-th layer $\delta_{i,\,m}/R_m$ is calculated according to the formula (20).

3. The value of the coefficient of time transformation $K_{i,\tau}$ is calculated by the formula (22).
4. The value of the criterion F_0 is calculated for each layer using the formula (21):

$$\left(F_0\right)_i = a_{\max} \cdot K_{i,\tau} \cdot \tau / R_м^2.$$

5. The initial temperature in the multi-layer plate in the process of heating is calculated for the specified values of the coordinates and time using the formula and nomogram given in [1, 14, 16].

5. Calculation example

The heating of a two-layer plate needs to be calculated on the condition that at the initial moment, the temperature of the layers is the same and is 20 ^{0}C, at the left boundary ($X = 0$), the temperature at the initial moment becomes 600 ^{0}C, at the right boundary there is no heat exchange (heat flow equals zero).

The thickness and thermal physical characteristics for the plates are:

– for the first layer:

$$\delta_1 = 0.06\ m;\ \lambda_1 = 1.094\ watt/m^{-1} \cdot {}^0C^{-1};\ c_1 = 0.464\ watt \cdot h \cdot kg^{-1} \cdot {}^0C^{-1};$$

$$\rho_1 = 1900\ kg \cdot m^{-3};\ a_1 = 1.237 \cdot 10^{-3}\ m^2 \cdot h^{-1};$$

– for the second layer:

$$\delta_2 = 0.15\ m;\ \lambda_2 = 0.0931\ watt/m^{-1} \cdot {}^0C^{-1};\ c_2 = 0.638\ watt \cdot h \cdot kg^{-1} \cdot {}^0C^{-1};$$

$$\rho_2 = 220\ кγ \cdot m^{-3};\ a_2 = 0.661 \cdot 10^{-3}\ m^2 \cdot h^{-1}.$$

The solution of this task is found according to the above method, i. e. by moving from heating of a single-layer plate with specified boundary conditions [6, 17]. In order to use the well-known solution, it is necessary to transform a two-layer plate into a single-layer one. For that, the value a_{max} will be accepted as the calculation value, i. e. for the first layer $a_{\max} = 1.237 \cdot 10^{-3}\ h^{-1}$. Then, using the formula (17) we determine the modified thickness of the second layer:

$$\delta_{2,м} = \delta_2 \sqrt[3]{\frac{c_2}{c_1}} = 0.15 \sqrt[3]{\frac{0.55}{0.4}} = 0.1668.$$

Using the formula (20), we determine the overall thickness of the modified layer:

$$R_m = \delta_1 + \delta_{2,m} = 0.06 + 0.1668 = 0.2268.$$

Using the formula (21), we determine the criterion F_0:

$$(F_0)_i = a_{\max} \cdot K_{i,\tau} \cdot \tau_i / R_m^2 = 1.237 \cdot 10^{-3} / 0.2268^2 \cdot \tau_i = 0.02405 \cdot \tau_i.$$

In order to satisfy the condition of homochronity for the two-layer plate, it is necessary to determine the value of the transformation coefficient $(K_i)_\tau$ for each layer according to the formula (22).

For the first layer it is

$$K_{i,\tau} = 1.237 \cdot 10^{-3} / 0.661 \cdot 10^{-3} = 1.871;$$

for the second layer

$$K_{2,\tau} = 0.661 \cdot 10^{-3} / 0.0661 \cdot 10^{-3} = 1.$$

Therefore, in the calculation of the heating of the first layer the value of the criterion $(F_{0.1})_m$ is

$$(F_{0.1})_m = 0.02405 \cdot 1871\tau = 0.045\tau;$$

for the second layer the value of the criterion

$$(F_{0.2})_m = 0.02405\tau.$$

Then, using the graph and the calculation formula [1, 14] we determine a change in a temperature field in the obtained single-layer plate for various section coordinates. In Fig. 4 there are graphs of heating of the two-layer plate under investigation that are obtained using the developed method and numerical method [15, 16].

Fig. 4 shows that the calculation results are in good agreement in a wide range of temperature and time. The time changed from 0 to 30 h ($0<F_0<1.57$). The maximum divergence of the obtained results does not exceed 15 % as related to the numerical calculations.

The maximum divergence is observed at the boundary of the layer contact, while for the other sections of the examined two-layer plate, the maximum divergence does not go above 10 %.

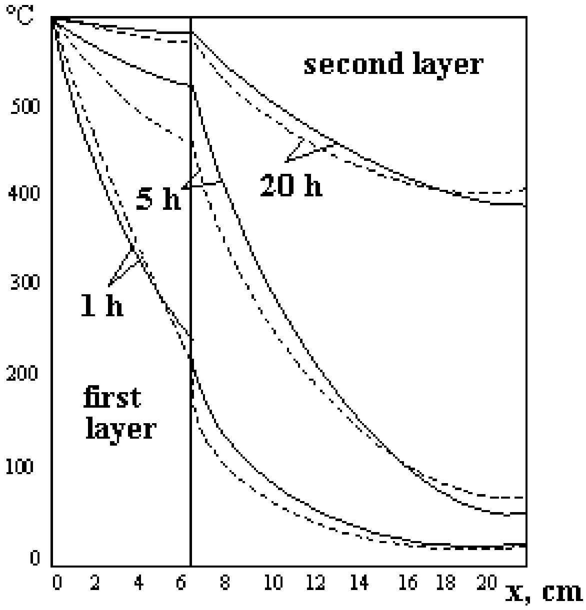

Fig. 4. Graphs of a change in the heating temperature of a two-layer plate for various moments of time: —— calculation by means of the numerical method; —— calculation using the suggested method; *x* — thickness of the plate

Conclusions

Based on the research presented in this paper, it was for the first time proven that the dimensionality of heat conduction coefficient in unsteady heat conduction is defined as kJ/m^3 · h · ^{0}C; thus, the dimensionality of heat conduction coefficient (relaxation coefficient of changes in the temperature of the solid body) is defined as 1/h.

Based on that, a modified equation for Fourier's heat conduction has been obtained, based on which methods for the calculation of the heating of multi-layer constructions which reduce to heating of a single-layer plate. Solutions, graphs and nomograms available in the literature on unsteady heat conduction for single-layer plates can be used in the process of calculation of the heating of constructions of this kind.

The calculation example indicates that the suggested method is highly efficient in its practical application and proves to be highly accurate in engineering practices.

References

1. A. V. Lykov, *Theory of Heat Conductivity* (Moscow, 1967) [in Russian].
2. S. G. Beregovoy, Ya. S. Podstrigach, "On Heat Conductivity of Multilayer Shells", Proceedings of Academy of Science of USSR. Solid Mechanics, N 3 (1972), 105—110.

3. B. M. Budak, A. A. Samarsky, A. I. Tikhonov, *Collection of Problems on Mathematical Physics* (Moscow, 1972) [in Russian].
4. Kh. S. Carslaw, J. C. Jaeger, *Conduction of Heat in Solids* (Moscow, 1964) [in Russian].
5. M. G. Kogan, "Unsteady State Heat Conduction in a Layered Medium", ZhTF [Journal of Technical Physics], vol. 27, N 3 (1974), 522—531.
6. V. A. Makagonov, "On Possibility to Reduce Multilayer Structures to Single-Layer Structures in Heat Calculations", Proceedings of Universities. Construction and Architecture, N 4 (1974), 137—140.
7. A. M. Zaytsev, "A Study of Temperature Conditions in Multilayer Walls at Variable Heat Flow", Proceedings of Universities. Construction and Architecture, N 2 (1974), 114—118.
8. A. M. Zaytsev, G. N. Krikunov, A. I. Yakovlev, *Calculation of Fire Resistance of Building Structure Elements* (Voronezh, 1982) [in Russian].
9. A. M. Zaytsev, "A Method for Calculation of Multilayer Structure Heating by Reducing to Single-Layer Plate on the Basis of Modified Fourier's Equation of Unsteady Heat Conduction", Fire and Explosion Safety, N 3 (2006), 55—61.
10. M. A. Mikheyev, I. M. Mikheeva, *Heat Transfer Principles* (Moscow, 1973) [in Russian].
11. B. S. Petukhov (ed.) *Heat Exchange Theory. Terminology. Collection of Recommended Terms* (Moscow, 1971) [in Russian].
12. G. F. Muchnik, I. B. Rubashov, *Methods of Heat Exchange Theory*, vol. 1, *Heat conduction* (Moscow, 1970) [in Russian].
13. M. M. Balashov, *About nature* (Moscow, 1991) [in Russian].
14. A. I. Pekhovich, V. M. Zhidkikh, *Calculations of Heat Conditions of Solids* (Leningrad, 1966) [in Russian].
15. *Recommendations on Calculation of Ultimate Fire Resistance of Concrete and Ferroconcrete Structures* (Moscow, 1986) [in Russian].
16. *Instruction on Calculation of Actual Limits of Fire Resistance of Ferroconcrete Building Structures on the Basis of Computer Application* (Moscow, 1975) [in Russian].