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Research paper

Research on Calculation Methods of Building Envelope Thermal Characteristics

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Abstract

Building envelope functional performance largely depends on the temperature fluctuation range on the interior surface. The aim of the calculation is to ensure that building envelope has the necessary thermal characteristics, which ensure maintaining almost stable temperature on the interior surface of the construction, under the periodic changes of environmental parameters. The dynamic thermal characteristics can also be used in the calculation of: the internal temperature in a room; the daily peak power and energy needs for heating or cooling; the effects of intermittent heating or cooling, etc. Exact prediction of building envelope temperature conditions under periodic thermal effects allows avoiding thermal failures. Calculation methods in the Ukraine state construction standards are significantly simplified. Currently, with return to furnace heating and other kinds of periodic heating, international standard calculation method is more important and requires revising the Ukrainian normative base.

Keywords: *density of heat flow rate; period of the variations; specific heat capacity; thermal resistance*

1. Introduction

Houses, where people stay, should ensure a defined comfort level. State of comfort is a subjective feeling people have under the complex influence of such main factors as acoustics, colour, temperature, humidity, air motion etc [1,2]. In addition, economic efficiency of technical solutions should be taken into account.
The main factors, which form indoor climate are temperature, air motion speed, humidity and radiant temperature (that is the average surface temperature of the building envelope and objects) [3,4].
Outside air temperature fluctuations (sun effect, diurnal variation of temperature) set additional temperature requirements for building envelope in summer period).
Building envelope functional performance largely depends on the temperature fluctuation range on the interior surface [5]. When the temperature fluctuation amplitude on the building envelope interior surface is large, periodic temperature rise of inside air can occur during the summer period with further heat transfer inside the building and overheating of the rooms. Thermal capacity of building envelope internal surfaces is calculated for evaluating indicators of microclimate comfort in the building.

The aim of the calculation is to ensure that building envelope has the necessary thermal characteristics, which ensure maintaining almost stable temperature on the interior surface of the construction, under the periodic changes of environmental parameters.

2. Main body

2.1. General

The dynamic characterization of a building component is obtained through parameters that identify its behaviour when it is subjected to loadings that are variable in time [6,7]
The dynamic thermal characteristics of a building component describe the thermal behaviour of the component when it is subject to variable boundary conditions, i.e. variable heat flow rate or variable temperature on one or both of its boundaries [8].
The dynamic thermal characteristics can also be used in the calculation of:

- the internal temperature in a room;
- the daily peak power and energy needs for heating or cooling;
- the effects of intermittent heating or cooling, etc.

According to UNE-EN ISO 13786: 2011 dynamic thermal characteristics of any component are four periodic thermal conductances and two heat capacities.
Periodic thermal conductance, *Lmn*, is the complex number relating the periodic heat flow into a component to the periodic temperatures on either side of it under sinusoidal conditions.
Lmm relates the periodic heat flow on side *m* to the periodic temperature on side *m* when the temperature amplitude on side *n* is zero. *Lmn* relates the periodic heat flow on side *m* to the periodic temperature on side *n* when the temperature amplitude on side *m* is zero.
Heat capacity, *Cm*, is the modulus of the net periodic thermal conductance divided by the angular frequency.

According to Ukrainian standards, the effects of outside air temperature fluctuation on the temperature conditions of building envelope during the summer period are calculated using the following factors:
- outside air temperature fluctuation amplitude Аt3роз, °C; it is the maximum deviation of temperature on the interior surface of non-transparent building envelope from the average daily temperature with the sun effect in the summer period;
- the decay rate of outside air temperature fluctuation amplitude v;
- heat absorption coefficient of material in particular layers s, W/(m2K); it is a physical parameter which represents the ability of the material to absorb heat during temperature fluctuations on its surface. It is calculated by ratio of the amplitude of heat flow rate fluctuation (W) to the amplitude of temperature fluctuation (K) on a unit of surface area of the material (m2) over the 24-hour period [9].

Significant air temperature fluctuations in the winter period and operation of heating appliances can cause extreme temperature changes inside the building. For ensuring comfortable indoor climate during the winter period, it is necessary to calculate thermal resistance. Thermal resistance of a building, according to the state standard of Ukraine ДСТУ-Н Б В.2.6-190:2013, is calculated by the following factors:
- indoor temperature fluctuation amplitude A_{t_i},°C;
- heat absorption coefficient Вj, $W/(m^2 \cdot K)$;
- heat absorption coefficient of particular layers of material S, $W/(m^2 \cdot K)$.

2.2. Procedure

The procedure in UNE-EN ISO 13786: 2011 applies to building components consisting of plane homogeneous layers. Thermal bridges usually present in such building components do not affect significantly the dynamic thermal characteristics, and can hence be neglected.

The calculation of dynamic thermal characteristics of non-plane components and of components containing very important thermal bridges shall be made by solving the equation of heat transfer under periodic boundary conditions.

The procedure is as follows:

a) identify the materials comprising the layers of the building component and the thickness of these layers, and determine the thermal characteristics of the materials;

b) specify the period of the variations at the surfaces;

c) calculate the penetration depth for the material of each layer;

d) determine the elements of the heat transfer matrix for each layer;

e) multiply the layer heat transfer matrices, including those of the boundary layers, in the correct order, so as to obtain the transfer matrix of the component.

Heat transfer matrix of a homogeneous layer.

The periodic penetration depth for the material of the layer, δ, is calculated from its thermal properties and the period T using Equation:

$$\delta = \sqrt{\frac{\lambda T}{\pi \rho c}} \tag{1}$$

The ratio of the thickness of the layer to the penetration depth is then

$$\xi = \frac{d}{\delta} \tag{2}$$

The matrix elements, *Zmn*, are calculated as follows:

$$\begin{aligned}
Z_{11} &= Z_{22} = \cosh(\xi)\cos(\xi) + j\sinh(\xi)\sin(\xi);\\
Z_{12} &= -\frac{\delta}{2\lambda}\left\{\sinh(\xi)\cos(\xi) + \cosh(\xi)\sin(\xi) + j\left[\cosh(\xi)\sin(\xi) - \sinh(\xi)\cos(\xi)\right]\right\};\\
Z_{21} &= -\frac{\lambda}{\delta}\left\{\sinh(\xi)\cos(\xi) - \cosh(\xi)\sin(\xi) + j\left[\sinh(\xi)\cos(\xi) + \cosh(\xi)\sin(\xi)\right]\right\}.
\end{aligned} \tag{3}$$

Heat transfer matrix of a building component

The heat transfer matrix of the building component from surface to surface is

$$Z = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} = Z_N Z_{N-1} \ldots Z_3 Z_2 Z_1 \tag{4}$$

where Z_1 Z_2, Z_3, ..., Z_N, are the heat transfer matrices of the various layers of the building component, beginning from layer 1. As a convention for building envelope components, layer 1 shall be the innermost layer.

The heat transfer matrix from environment to environment through the building component is

$$Z_{ee} = Z_{s2} Z Z_{s1}$$

where Z_{s1} and Z_{s2} are the heat transfer matrices of the boundary layers, given by

$$Z_\text{s} = \begin{pmatrix} 1 & -R_\text{s} \\ 0 & 1 \end{pmatrix} \tag{5}$$

where *Rs* is the surface resistance of the boundary layer, including convection and radiation.

The method given in this International Standard is based on heat conduction in building components composed of several plane, parallel, homogeneous layers, under regular sinusoidal boundary conditions and one dimensional heat flow.

That means that at any location in the component, the temperature variations can be modelled by

$$\theta_n(x,t) = \bar{\theta}(x) + \frac{\hat{\theta}_{+n}(x)e^{j\omega t} + \hat{\theta}_{-n}(x)e^{-j\omega t}}{2} \tag{6}$$

and the variations of the density of heat flow rate are

$$q_n(x,t) = \bar{q}(x) + \frac{\hat{q}_{+n}(x)e^{j\omega t} + \hat{q}_{-n}(x)e^{-j\omega t}}{2} \tag{7}$$

with

$$\hat{\theta}_\pm(x) = \left|\bar{\theta}(x)\right| e^{\pm j\psi} \quad \text{and} \quad \hat{q}_\pm(x) = \left|\hat{q}(x)\right| e^{\pm j\varphi} \tag{8}$$

Temperature and density of heat flow rate variations are those around the mean values *0* and *cj* of these variables, which are linked by

$$\bar{q} = U\left(\bar{\theta}_i - \bar{\theta}_e\right) \tag{9}$$

where *U* is the thermal transmittance of the component.

The one dimensional equation of heat can be solved for a single layer of homogenous material with sinusoidal boundary conditions. The solution can be represented by Equation (10), the element being represented by the heat transfer matrix.

$$Z = \begin{pmatrix} \hat{\theta}_2 \\ \hat{q}_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \cdot \begin{pmatrix} \hat{\theta}_1 \\ \hat{q}_1 \end{pmatrix} \quad (10)$$

The heat transfer matrix, *Z*, then allows the calculation of the variations of the temperature, θ_2, and of the density of heat flow rate, q_2, on one side of the building component, when these quantities, θ_1, and q_1, are known on the other side.
The elements of the heat transfer matrix have the physical interpretation indicated below. Each element is a complex number, which can be represented by its modulus, $|Z_{mn}|$, and its argument, $\varphi_{mn} = \arg(Z_{mn})$.

- $|Z_{11}|$ is a temperature amplitude factor, i.e. the amplitude of the temperature variations on side 2 resulting from an amplitude of 1 K on side 1.
- φ_{11} is the phase difference between temperatures on both sides of the component.
- $|Z_{21}|$ gives the amplitude of the density of heat flow rate through side 2 resulting from a periodic variation of temperature on side 1 with an amplitude of 1 K.
- φ_{21} is the phase difference between the density of heat flow rate through side 2 and the temperature of side 1.
- $|Z_{12}|$ gives the amplitude of the temperature on side 2 when side 1 is subjected to a periodically varying density of heat flow rate with an amplitude of 1 W/m^2.
- φ_{12} is the phase difference between the temperature on side 2 and the density of heat flow rate through side 1.
- $|Z_{22}|$ is the heat flow rate amplitude factor, i.e. the amplitude of the variations of the density of heat flow rate through side 2 resulting from an amplitude of density of heat flow rate of 1 W/m^2 through side 1.
- φ_{22} is the phase difference between the densities of heat flow rate through both sides of the component.

The time delays between the maximum of an effect and the maximum corresponding cause can be calculated from the phase shift of the transfer matrix element, Z_{ij}:

$$\Delta t_{ij} = \frac{T}{2\pi}\varphi_{ij} = \frac{T}{2\pi}\arg\left(Z_{ij}\right) \quad (11)$$

The applications of the dynamic thermal characteristics are numerous.
The heat transfer matrix, Z, can be used for any application linking the boundary conditions on one side to the temperature and heat flow on the other side, as shown in Equation (10).
For example, the heat flow rate required to maintain a constant temperature on side 2 despite temperature and heat flow rate variations on side 1 is given by

$$\hat{q}_2 = Z_{21}\hat{\theta}_1 + Z_{22}\hat{q}_1 \quad (12)$$

Similarly, the variation of the temperature on side 2 can be obtained by

$$\hat{\theta}_2 = Z_{11}\hat{\theta}_1 + Z_{12}\hat{q}_1 \quad (13)$$

The variations of heat flow rate entering into the component on both sides can be calculated from the variations of temperatures by solving Equation (10) for the densities of heat flow rates

$$\begin{pmatrix} \hat{q}_1 \\ -\hat{q}_2 \end{pmatrix} = \frac{1}{Z_{12}}\begin{pmatrix} -Z_{11} & 1 \\ 1 & -Z_{22} \end{pmatrix} \cdot \begin{pmatrix} \hat{\theta}_1 \\ \hat{\theta}_2 \end{pmatrix} \quad (14)$$

Thermal admittance is the amplitude of the density of heat flow rate on one side resulting from a unit temperature amplitude on the same side, when the temperature amplitude on the other side is zero:

$$Y_{11} = \frac{\hat{q}_1}{\hat{\theta}_1} \quad \text{for} \quad \hat{\theta}_2 = 0, \quad \text{so} \quad Y_{11} = -\frac{Z_{11}}{Z_{12}} \quad (15)$$

$$Y_{22} = \frac{-\hat{q}_2}{\hat{\theta}_2} \quad \text{for} \quad \hat{\theta}_1 = 0, \quad \text{so} \quad Y_{22} = -\frac{Z_{22}}{Z_{12}} \quad (16)$$

Periodic thermal transmittance is amplitude of the density of heat flow rate on one side when the temperature amplitude on that side is zero and there is unit temperature amplitude on the other side:

$$Y_{12} = \frac{\hat{q}_2}{\hat{\theta}_1} \quad \text{for} \quad \hat{\theta}_2 = 0, \quad \text{so} \quad Y_{12} = -\frac{1}{Z_{12}} \quad (17)$$

The principles of envelope Y surface thermal absorption coefficient calculation, stated in the Ukraine state construction standards, are based on the professor Vlasov's theory.
The envelope material heat absorption coefficient S characterizes its ability to absorb heat during temperature fluctuations on the surface. The value of the coefficient depends on thermophysical properties of the material (λ, c, p) and cyclic frequency of temperature fluctuation w=2 π/T

$$S = \sqrt{\frac{2\cdot\pi\cdot\lambda\cdot c\cdot\rho}{T}}, \quad (18)$$

where λ is the coefficient of heat conductivity of the material, $W/(m^2\cdot K)$; *c* is the heat capacity J/(kg$\cdot K$); *p* is the material density, kg/m^3.
It is clear that the *S* coefficient in the specified base time interval *T* depends purely on properties of the material, therefore it can be considered as a physical property of the envelope material.
Normally in thermo-technical calculations of the envelope the fluctuation period is *T* = 24 hours (except for the floor), so

$$S_{24} = 0{,}51\sqrt{\lambda \times c \times \rho}. \quad (19)$$

Y_{int} calculation begins with determination of conventional thickness of the first layer, starting the numeration from the interior surface of the envelope.
a) if the interior layer of the building envelope has thermal inertia $D \geq 1$, then

$$Y_{int} = s_1 \quad (20)$$

b) if thermal inertia of the first layer of the building envelope is $D < 1$, and the first and the second layers of the construction is $D1 + D2 \geq 1$, then the heat absorption coefficient of the surface is calculated be the formula

$$Y_{\text{int}} = \frac{R_1 s_1^2 + s_2}{1 + R_1 s_2}; \quad (21)$$

where R_1, s_1, s_2 are heat resistance coefficient and heat absorption coefficients of the first and the second layers accordingly;
c) if thermal inertia of the first *n* layers of the construction is $D1 + D2 + \ldots + Dn < 1$, but thermal inertia of *n+1* layers is $D1 + + D2 + \ldots + Dn + Dn{+}1 \geq 1$, then heat absorption coefficient of the interior surface is calculated taking into account heat absorption coefficients of *n* layers by the formulas for the *n*-th layer

$$Y_n = \frac{R_n \cdot s_n^2 + s_{n+1}}{1 + R_n \cdot s_{n+1}}; \quad (22)$$

for the i-th layer ($i = n - 1; n - 2;...; 1$)

$$Y_i = \frac{R_i \cdot s_i^2 + Y_{i+1}}{1 + R_i \cdot s_{i+1}}; \tag{23}$$

For inhomogeneous layers of the construction it is necessary to calculate the average coefficient of heat absorption of the layer material S_{avg}, $W/(m^2 \cdot K)$, by the formula

$$s_{av} = \frac{\sum_{n=1}^{n} s_n F_n}{\sum_{n=1}^{n} F_n}; \tag{24}$$

where s_n is the heat absorption coefficient of materials in the layer, $W/(m^2 \cdot K)$;
F_n is the area taken by particular materials on the surface of the layers, m^2;
d) if thermal inertia of all the layers of the construction is less than 1, then heat absorption coefficient of interior surface is calculated from the last n-th layer by the formula

$$Y_n = \frac{R_n \cdot s_n^2 + \alpha_{зн}}{1 + R_n \cdot \alpha_{зн}}; \tag{25}$$

Next, Y_{n-1} is calculated by the formula

$$Y_{n-1} = \frac{R_{n-1} \cdot s_{n-1}^2 + Y_n}{1 + R_{n-1} \cdot Y_n}. \tag{26}$$

If the construction contains air spaces, we can assume that for them $s = 0$.
for envelopes almost without heat capacity (e.g. transparent envelope structure) the interior surface heat absorption factor is calculated by the formula for one-layer envelope

$$Y_{\text{int}} = \frac{R \cdot s^2 + \alpha_{ext}}{1 + R \cdot \alpha_{ext}}. \tag{27}$$

Given that $s = 0$, then

$$Y_{\text{int}} = \frac{\alpha_{ext}}{1 + R\alpha_{ext}} = \frac{1}{1{,}08 R_{\Sigma c}}; \tag{28}$$

where $R_{\Sigma c}$ is heat transmission resistance of the transparent construction, m^{2}K/W.
In this case, heat absorption coefficient B equals heat transfer coefficient of the construction

$$B = \frac{1}{\frac{1}{\alpha_{\text{int}}} + \frac{1}{Y_{\text{int}}}} = \frac{1}{\frac{1}{\alpha_{\text{int}}} + \frac{1 + R\alpha_{ext}}{\alpha_{ext}}} = \frac{1}{\frac{1}{\alpha_{\text{int}}} + R + \frac{1}{\alpha_{ext}}} = \kappa. \tag{29}$$

f) If an interior wall separates two heated living spaces and has conditional thickness less than two, then the wall is separated through its thickness into two parts with equal conditional thicknesses. Calculation begins with the layer containing the margin of separation. Heat absorption of the layer is

$$Y_{\text{int}} = \frac{R_m \cdot s_m^2 + 0}{1 + R_m \cdot 0} = R_m \cdot s^2, where \quad R_m = \frac{\delta_m^{/}}{\lambda_m}, \tag{30}$$

δ /m is the thickness of the layer before the margin of separation. Beyond:

$$Y_{m-1} = \frac{R_{m-1} \cdot s_{m-1}^2 + Y_m}{1 + R_{m-1} \cdot Y_m}. \tag{31}$$

Heat absorption coefficient Bj of the interior surface j-th of non-transparent building envelope structure equals fluctuation amplitude of the heat flow rate passing through the envelope surface at the fluctuation amplitude of the inside air temperature At = 1°C and is calculated by the formula

$$B = \frac{1}{\frac{1}{\alpha_{\text{int}}} + \frac{1}{Y_{\text{int}}}}. \tag{32}$$

2.3. Examples

An example of calculating a multilayered component using the method of UNE-EN ISO 13786: 2011.
A concrete wall is insulated outside with 100 mm polystyrene foam coated with a convenient finishing.

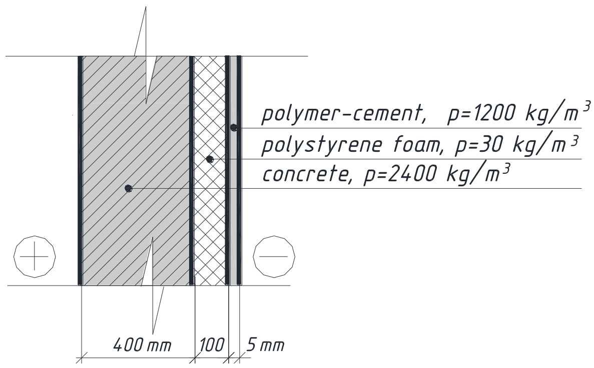

Fig. 1: Design model

Material properties are given in Table 1.

Table 1: Thermal properties of materials

Material	λ W/(m·K)	ρ kg/m3	*c* J/(kg K)	*d* m	*R* m2·K/W	*a* mm2/s	*δ* m	ξ —
Internal surface	—	—	—	—	0,130	—	—	—
Concrete	1,80	2 400	1 000	0,200	0,111	0,75	0,144	1,393
Thermal insulation	0,04	30	1 400	0,100	2,500	0,95	0,162	0,618
Coating	1,00	1 200	1 500	0,005	0,005	0,56	0,124	0,040
External surface	—	—	—	—	0,040	—	—	—

Elements of the matrix Z_{mn}, calculated by the formula (3) for each layer, are shown in Table 2.

Table 2: The matrix elements, *Zmn* The heat transfer matrices of the boundary layers:

$$Z_{s1}=\begin{pmatrix}1 & -0,04\\ 0 & 1\end{pmatrix};Z_{s2}=\begin{pmatrix}1 & -0,13\\ 0 & 1\end{pmatrix}$$

The heat transfer matrix of the building component from surface to surface is:

$$z_{11}=1+0,0016j \qquad z_{12}=-0,005-0,0000026j$$
$$z_{21}=0,0003-0,645j \qquad z_{22}=1+0,0016j$$

The results of calculation are in Tables 3 to 5.

Table 3: Elements of the heat transfer matrices in both directions

	Element of matrix	Modulus	Time shift (in range -12 до h to 12 h) H
Heat transfer matrix	Z_{11}	98,12	8,96
	Z_{21}	83,07 W/(m²·K)	0,99
	Z_{12}	16,51 m²·K/W	-3,89
	Z_{22}	13,99	-11,86
Inverse matrix	Z_{11}	13,99	-11,86
	Z_{21}	83,07 W/(m²K·)	-11,01
	Z_{12}	16,51 m²K·/W	8,11
	Z_{22}	98,12	8,96

Table 4: Dynamic thermal characteristics

Property	Modulus	Time shift h
Internal thermal admittance, *Y11*	5,94 W/(m2·K)	0,85
External thermal admittance, Y22	0,85 W/(m2·K)	4,03
Periodic thermal transmittance, Y12	0,061 W/(m2·K)	-8,11
Internal areal heat capacity, *κ1*	82 kJ/(m2 K)	—
External areal heat capacity, *κ2*	12 kJ/(m2·K)	—
Thermal transmittance, *U*	0,359 W/(m2·K)	—
Decrement factor, f	0,169	—

The calculation of heat absorption of the concrete wall surface with exterior thermal insulation according to the scheme on Picture 1 by the Ukraine state construction standard ДСТУ-Н Б В.2.6-190:2013 method.

In the calculation, the main layers of the building construction (starting from the interior layer) are taken into consideration. Their main thermophysical characteristics are specified in Table 1. Design coefficients of materials heat absorption of the building envelope layers for operating conditions A according to the Ukraine state construction standard ДСТУ Б В.2.6-189:2013 :

- Concrete $S_1 = 16{,}77\ \mathrm{W/m2 \cdot K}$;
- Thermal insulation $S_2 = 0{,}34\ \mathrm{W/m2 \cdot K}$
- Coating $S_3 = 5{,}56\ \mathrm{W/m2 \cdot K}$;

Thermal inertia calculation for each layer of the construction is carried out in accordance with the formula (5) and is specified in Table 5.

Table 5: Thermal inertia calculation for each layer of the construction

Layer number	Symbol	Quantity	Calculation formula
1	D1	1,861	D1 = R1s1 = 0,111·16,77 = 1,861
2	D2	0,85	D2 = R2s2 = 2,5·0,34 = 0,85
3	D3	0,028	D3 = R3s3 = 0,005·5,56 = 0,028

Thermal inertia of the interior layer of the building envelope is $D \geq 1$; therefore, the floor surface thermal absorption factor Y_{int} is calculated by the formula (20) and equals:

$Y_{int} = 16{,}77\ \mathrm{W/m2 \cdot K}$;

Heat absorption coefficient *Bj* by the interior surface of the *j*-th non-transparent building envelope is calculated by the formula (32):

Concrete	$z_{11}=0,379+1,858j$	$z_{12}=-0,097-0,075j$
	$z_{21}=22,16-30,55j$	$z_{22}=0,379+1,858j$
Thermal insulation	$z_{11}=0,976+0,381j$	$z_{12}=-2,491-0,318j$
	$z_{21}=0,039-0,304j$	$z_{22}=0,976+0,381j$
Coating	$z_{11}=1+0,0016j$	$z_{12}=-0,005-0,0000026j$
	$z_{21}=0,0003-0,645j$	$z_{22}=1+0,0016j$

$$B=\frac{1}{\frac{1}{8,7}+\frac{1}{16,77}}=5,73W/m^2\cdot K.$$

Methodology in the Ukraine state construction standard ДСТУ-Н Б В.2.6-190:2013 calculates only one factor out of the specified dynamic characteristics.

3. Conclusions

Calculation method in the ДСТУ-Н Б В.2.6-190:2013 is based on simplifications and contains conservative predictions of constructions thermal characteristics increase. At the moment, with return to furnace heating and other periodic heating methods, it is important to predict exact temperature and humidity conditions of constructions. UNE-EN ISO 13786: 2011 calculation method becomes essential and requires revising the corresponding Ukrainian normative base. Results that are more accurate can be achieved by A. Shklover's method (at scientific-theoretical research of periodic thermal effects), but it must be revised according to modern requirements for energy efficiency and new building envelope construction solutions.

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