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THE EFFECT OF THE FOURIER NUMBER ON CALCULATION OF AN UNSTEADY HEAT TRANSFER OF BUILDING WALLS

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Abstract. When the temperature changes in any side of construction, the heat flow diffusing through construction also changes and it is varying until the stabilized steady state conditions is reached. In real terms, the heat exchange process in buildings is an unsteady state, consequently varying in time. Volatility of the heat exchange process is influenced by oscillating external temperature, internal heat gains, solar radiation and other factors that affect the heat balance of building. While calculating unsteady heat exchanges, it is important to divide the material into the right number of conditional layers. A conditional layer is material's thickness, in which an assumed process of steady heat transfer takes place. The time step is the second parameter which affects the accuracy of calculation of unsteady heat transfer. This parameter defines time during which temperature diffuses step by step through the conditional layer. Thermal diffusivity is the last parameter, which defines the equalization speed of the temperature in conditional layer. A combination of all these parameters is expressed as the Fourier number.

Our research has showed that it's rational to divide layers of enclosure into equal thermal diffusions. Also, the cooling (heating) speed and the acceleration values of conditional layers significantly affect the accuracy of calculation.

Keywords: unsteady heat transfer, Fourier number, cooling (heating) speed, cooling (heating) acceleration, conditional layer, thermal diffusion, Hot box.

1. Introduction

For building heating it is consumed about 80% of the total thermal energy consumption of building. Exploitation expenses depend on how effective the external wall solution has been chosen (Zavadskas *et al.* 2008). One of initiatives to reduce energy consumption is the EU Directive 2002/91/EC Energy performance of Buildings, which makes it obligatory (Wargocki *et al.* 2008). The production of thermal energy by regular, liquid, solid or gaseous fuels, generates negative impact to the environment – by releasing of carbon dioxide. Also an increase in the price of thermal energy is very important to the least possible use of thermal energy for building's heating while maintaining the regulated indoor climate parameters (Šeduikytė *et al.* 2008). One of the thermal energy saving ways is an intermittent space heating (Valančius *et al.* 2005). A relevant issue is to assess the time till heating system's freezing, when the accident happens in the heating networks. The identification of how much additional heating power is needed to restore normative temperature for various time intervals is also important for intermittent heating. In order to forecast the following questions it is needed to know the cooling and heating accumulation rates of building walls (Juodvalkis 2008) as well as of furniture and other objects taking place in the building rooms (Hensen *et al.* 2001).

Obviously, heat transfer processes in buildings are always unsteady under real conditions (Valančius *et al.* 2005).

Unsteady heat transfer can be characterized by the concept of heat transfer when heated (frozen) material's temperature varies continuously in time. In examining a simple case where the heat flow moves in one direction only, the differential heat conduction equation is expressed applying the finite difference method (Фокин 2006; Claesson 2003; Stankevičius *et al.* 2000; Богословский 1982):

$$\frac{\Delta\theta}{\Delta t} = a\frac{\Delta^2\theta}{\Delta x^2}, \tag{I}$$

where: $\Delta\Theta$ – changes of temperature over a time step, [°C]; Δt – time step, [s]; Δx – layer's thickness, [m].

For the solution of this equation the homogenous flat wall is divided into elementary Δx layers of equal thickness (Stankevičius *et al.* 2000). When the planes separating the layers are marked using numbers n–1; n; n+1 and the time is divided to the equal ranges Δt, the equation is expressed as follows (Фокин 2006; Stankevičius *et al.* 2000; Богословский 1982):

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$$\frac{\Theta_n^{t+1} - \Theta_n^t}{\Delta t} = a \cdot \frac{\Theta_{n+1}^t + \Theta_{n-1}^t - 2 \cdot \Theta_n^t}{\Delta x^2}. \quad \text{(II)}$$

A general formula for temperature's calculation in any plane at time interval Δt, when temperatures in the same plane and two surrounding planes in the preceding time Δt are known (Nevriva *et al.* 2009) is:

$$\Theta_n^{t+1} = \Theta_n^t + \frac{a \cdot \Delta t}{\Delta x^2} \cdot \left(\Theta_{n+1}^t - 2 \cdot \Theta_n^t + \Theta_{n-1}^t\right). \quad \text{(III)}$$

In partitions of building processes of the heat transfer may be determined by Fourier differential equation (Nikitin *et al.* 2006). In building physics Fourier number is defined as dimensionless parameter which characterizes the heat transfer. This number shows the condition of steady temperature's variation and is usable for calculations of enclosure of unsteady heat transfer. This is dimensionless time, which together with the Biot number characterizes transient heat transfer problems (Wang 2009; Shevchuk 2006). The expression of the Fourier number:

$$F_O = \frac{a \cdot \Delta t}{\Delta x^2}, \quad \text{(IV)}$$

where: a – thermal diffusivity [m^2/s]; Δt – time step [s]; Δx – layer's thickness [m].

By the case of unsteady heat transfer, in any plate the temperature is determined by the following formula:

$$\Theta_n^{t+1} = \Theta_n^t + F_O \cdot \left(\Theta_{n+1}^t - 2 \cdot \Theta_n^t + \Theta_{n-1}^t\right). \quad \text{(V)}$$

By the individual case, if the values of Δt and Δx are chosen such that $F_O = \frac{a \cdot \Delta t}{\Delta x^2} = 0.5$ (Iijima *et al.* 2004), then transformed equation (V) could be expressed as follows:

$$\Theta_n^{t+1} = \frac{\left(\Theta_{n+1}^t + \Theta_{n-1}^t\right)}{2}. \quad \text{(VI)}$$

According to scientists publications (Karbauskaitė *et al.* 2008; Stankevičius *et al.* 2000) the value of the Fourier number equal to 0.5 is the maximum permissible. Higher value of this number affects significant errors in the calculation of temperature. The best accuracy is achieved, when F_o = 1/6 = 0.1666, but as it is less, the size and time of calculation are increasing.

While calculating unsteady heat transfer, in each time step differences between calculated and exact values always takes place. In general case, three groups of „errors" exist (Hensen *et al.* 2001):

1. Truncation errors – this type of errors is given when the fluxions of differential equation (I) are changed into the finite elements. They can be reduced by reducing the time step Δt and increasing conditional layer's thickness Δx;
2. Rounding errors – which arise in calculating a significant number of decimal places. These errors can be reduced by using double precision arithmetic.
3. History errors – which are given due to errors introduced in preceding solution steps. This type of errors has the greatest influence to the accuracy of calculation. The error of the first time step affects the second time step calculation of temperature.

In this paper these problems are solved:

a) Creation of methodology for determination of optimal number of conditional layers, which are ofthe different materials of enclosure;
b) What size of inaccuracies is possible in large cooling (heating) speed and acceleration?
c) What are the optimal values of Fourier number?

2. The experimental research of thermal parameters of construction materials

Experimental research was performed in the accredited laboratory by using certified equipment. The medium-weight construction was chosen, consisting of two 25 mm thickness wood fibreboard panels (MDF) and one 50 mm thickness expanded polystyrene foam panel (EPS) (Fig. 1). For determination of the thermal conductivity λ of these materials the "conduction" device was used, whose principle is based on the constant heat flux over the whole area of the sample. Density ρ was determined by measuring weight and volume; the ratio of these parameters shows the density. Specific heat capacity c and the cooling rate were measured by calorimeter.

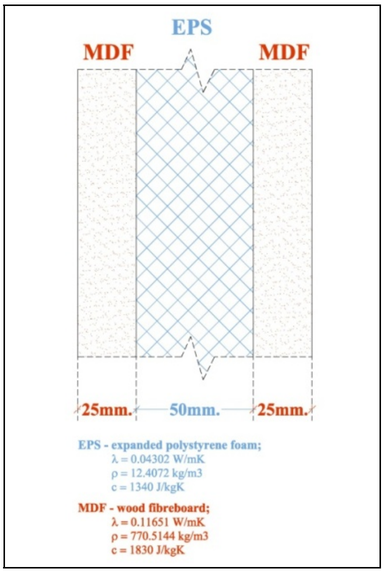

Fig. 1. Scheme of investigated construction in "Hot box"

2.1. Experimental research of construction in "Hot box"

Experimental research of construction was done in "Hot box" (Figs. 2 and 3) in order to estimate the unsteady heat transfer calculation composed by the spreadsheet.

During the research heating, cooling and their combinations were used on opposite sides of the construction and the temperatures of characteristic points were measured, such as: cold side air (Θ_e), surface of cold side (Θ_{se}) cold interface (Θ_1), warm interface (Θ_2), surface of warm side (Θ_{si}), warm side air (Θ_i) (Fig. 4). The temperature was measured in time steps of 3 minutes.

Fig. 2. General view of "Hot box“”

Fig. 3. Construction (sample) in "Hot box"

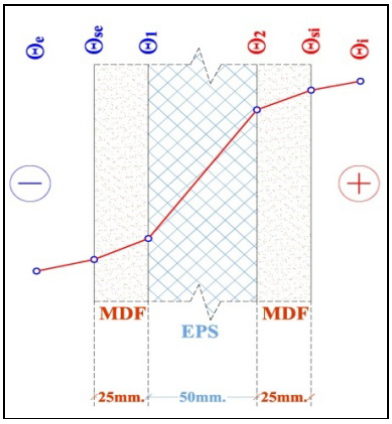

Fig. 4. Characteristic points of construction

This research was made using three heating modes:

1. Using the first heating mode, one side of the construction was supported by 20.5±0.5 °C temperature, other side was supported by –15.5±0.5 °C temperature. When steady state condition in all construction was established, the heating and cooling was disconnected and the temperature variation was recorded in characteristic points of construction (Fig. 5).
2. Using the second heating mode, one side of the construction was supported by 20.5±0.5 °C temperature, other side was supported by –15.5±0.5 °C temperature. Then the cooling was disconnected and the temperature variation was recorded in characteristic points of construction (Fig. 6).
3. Using the third heating mode, one side of the construction was supported by 20.5±0.5 °C temperature, other side's temperature was reduced from 20±0.5 to 15.5±0.5 °C (Fig. 7).

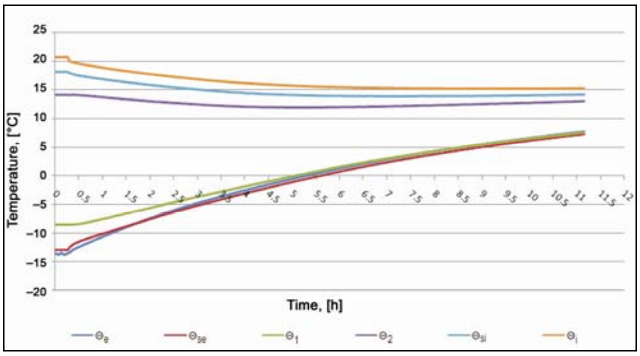

Fig. 5. First heating mode, here: Θ_e – air temperature of cold side, Θ_{se} – surface temperature of cold side, Θ_1 – temperature of cold interface, Θ_2 – temperature of warm interface, Θ_{si} – surface temperature of warm side, Θ_i – air temperature of warm side

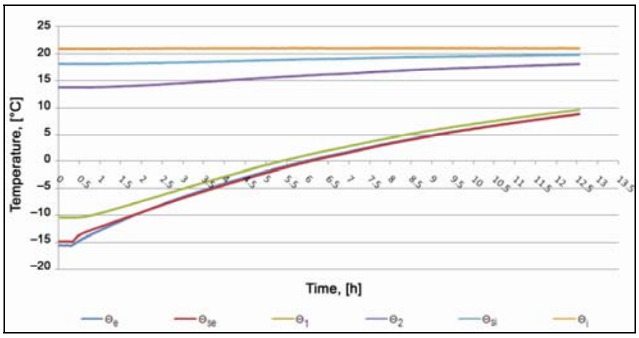

Fig. 6. Second heating mode, here: Θ_e – air temperature of cold side, Θ_{se} – surface temperature of cold side, Θ_1 – temperature of cold interface, Θ_2 – temperature of warm interface, Θ_{si} – surface temperature of warm side, Θ_i – air temperature of warm side

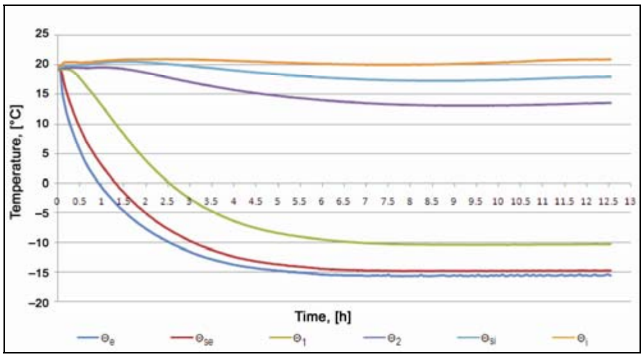

Fig. 7. Third heating mode, here: Θ_e – air temperature of cold side, Θ_{se} – surface temperature of cold side, Θ_1 – temperature of cold interface, Θ_2 – temperature of warm interface, Θ_{si} – surface temperature of warm side, Θ_i – air temperature of warm side

2.2. Spreadsheet of unsteady heat transfer

The calculation of unsteady heat exchanges was done with program in Excel environment. The calculation was performed according to experimental research in "Hot box” and the mentioned heating modes, which can be divided into three groups: double-sided defrost, one-sided defrost and one-sided cooling. In each case of heating mode, the spreadsheet was divided into three groups according to conditional layers’ thicknesses (Fig. 8):

1 layer MDF (wood fibreboard) + 1 layer EPS (expanded polystyrene foam);

3 layer MDF (wood fibreboard) + 1 layer EPS (expanded polystyrene foam);

5 layer MDF (wood fibreboard) + 2 layer EPS (expanded polystyrene foam).

The variation of the temperature can be monitored and recorded in time by changing the time step in spreadsheet.

Calculating procedure was performed by recording a Fourier number and calculated values of the temperature. These calculated values were compared with measured ones, as presented graphically. Conditional layers of construction’s materials are split into the parts in order to find the optimal Fourier number.

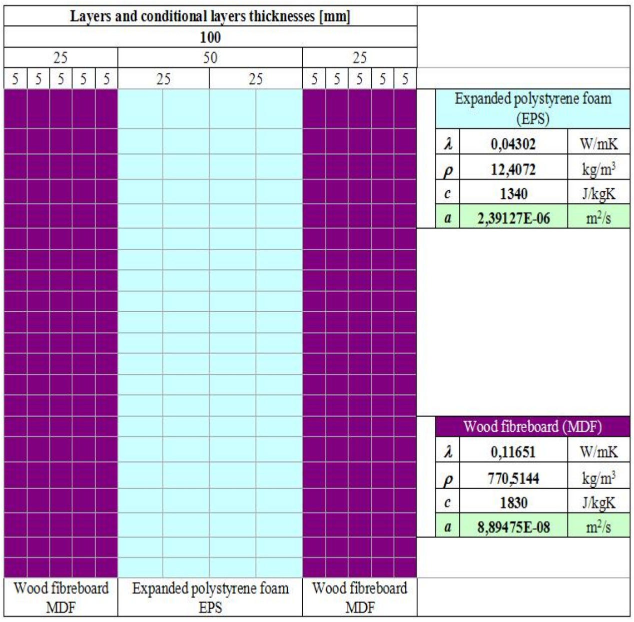

Fig. 8. Construction scheme of calculation

The calculation was done for each case of the heating mode by calculating the temperatures at surfaces Θ_{si}, Θ_{se}, materials interfaces $\Theta_{EPS/MDP}, \Theta_{MDP/EPS}$, conditional layers $\Theta_{EPS/MDP/1}, \Theta_{MDP/EPS/1}$; $\Theta_{EPS/MDP/2}$, $\Theta_{MDP/EPS/2}$ etc.

To ensure the reliability of calculation, the spreadsheet was updated with attached calculations evaluating air temperatures Θ_i, Θ_e and their influence to the convectional heat transfer coefficient’s values h_{si}, h_{se}. The comparison of calculated values of temperatures, including cold and warm sides’ air temperatures Θ_i, Θ_e and without air temperatures, it was accepted to keep the results of the spreadsheet without air temperatures.

2.3. Selection of the optimum number of conditional layers

Dividing materials of construction into conditional layers it is important to find the optimum number of these layers. According to the scientists’ publication (He *et al.* 2004; Hence *et al.* 2001), in order to get undistorted results of unsteady heat transfer calculation of heterogeneous wall, it is necessary that each Fourier number of materials would be equal:

$$F_{o,1} = F_{o,2} = F_{o,3} = ... = F_{o,n}\,. \tag{VII}$$

In our case Fourier number of wood fibreboard and expanded polystyrene foam must be equal:

$$F_o^{MDP} = F_o^{EPS}\,. \tag{VIII}$$

Extracted formula could be expressed as follows:

$$\frac{a_{MDP}\cdot\Delta t}{\Delta x_{MDP}^2} = \frac{a_{EPS}\cdot\Delta t}{\Delta x_{EPS}^2}\,. \tag{IX}$$

The time steps Δt in the formula (IX) are equal for both materials. Simplified formula:

$$\frac{a_{MDP}}{\Delta x_{MDP}^2} = \frac{a_{EPS}}{\Delta x_{EPS}^2}\,. \tag{X}$$

From (X) formula:

$$\Delta x_{MDP} = \sqrt{\frac{a_{MDP}\cdot\Delta x_{EPS}^2}{a_{EPS}}}\,; \tag{XI}$$

$$\Delta x_{EPS} = \sqrt{\frac{a_{EPS}\cdot\Delta x_{MDP}^2}{a_{MDP}}}\,. \tag{XII}$$

The general formulas for construction of two materials are:

$$\Delta x_1 = \sqrt{\frac{a_1\cdot\Delta x_2^2}{a_2}}\,; \tag{XIII}$$

$$\Delta x_2 = \sqrt{\frac{a_2\cdot\Delta x_1^2}{a_1}}\,. \tag{XIV}$$

Dividing materials of construction into the optimum number of conditional layers it is recommended to start from the material with a maximum value of thermal diffusivity. In our case, this is expanded polystyrene foam (EPS), which is divided by the increasing number of layers: 1, 2, 3, 4 and etc. (Table 1). The adequate thermal diffusion of wood fibreboard (MDF) is recalculated for each choice of conditional layers of EPS.

Table 1. Example of selection of the optimal number of conditional layers in heterogeneous construction

EPS d = 50 mm		MDF d = 25 mm	
Number of conditional layer (-s)	Thickness of conditional layer (-s) ***d***, [mm]	Number of conditional layer (-s)	Thickness of conditional layer (-s) ***d***, [mm]
1	50	2.27	11
2	**25**	**5**	**5**
3	16.7	6.25	4
4	12.5	8.33	3
5	10	12.5	2

The best choice is the number of conditional layers where all numbers are whole (marked in Table 1).

2.4. Thermal diffusion

Under the unsteady heat transfer case, the temperature diffuses in each material by particular speed. Thermal diffusion is a physical parameter, which shows the speed of temperature's equalization in particular thickness of material. It can be expressed by a ratio of thermal diffusivity and a square of layer's thickness:

$$\Lambda = \frac{a}{d^2}, [1/s], \tag{XV}$$

where: Λ – thermal diffusion, [1/s]; a – thermal diffusivity of material, [m^2/s] d – thickness of material, [m].

Thermal diffusion is proportional to the time constant of a layer, which is expressed as:

$$\tau_{sl} = \frac{C}{H} = \frac{\chi \cdot A}{U_{sl} \cdot A} = \frac{\chi}{U_{sl}} = \frac{\rho \cdot c \cdot d}{\frac{\lambda}{d}} = \tag{XVI}$$

$$\frac{\rho \cdot c \cdot d^2}{\lambda} = \frac{d^2}{a} = \frac{1}{\Lambda}, [s]$$

$$\Lambda = \frac{1}{\tau_{sl}}, [1/s], \tag{XVII}$$

where: λ – thermal conductivity, [W/(mK)]; ρ – density, [kg/m^3]; τ_{sl} – time constant of the internal layer, [s]; χ – specific heat of the layer, [J/(m^{2}K)]; H – heat loss coefficient, [W/K]; U_{sl} – heat transfer coefficient of the layer, [W/(m^2 K)].

2.5. Thermal diffusion of the building

Not only each of the material has thermal diffusion, it is also had by the construction made of materials:

$$\Lambda_t = \Lambda_1 + \Lambda_2 + ... + \Lambda_n, [1/s], \tag{XVIII}$$

where: Λ_t – total thermal diffusivity, [1/s]; Λ_1 – thermal diffusivity of the first material of construction, [1/s]; Λ_2 – thermal diffusivity of the second material of construction, [1/s]; Λ_n – thermal diffusivity of the nth material of construction, [1/s].

Formula (XVIII) may be adjusted to the building by multiplying thermal diffusion from the area of the construction and the temperature difference between outside and inside:

$$I_\Lambda = \sum \Lambda_t \cdot A \cdot \Delta\Theta, [\mathrm{m}^2 \cdot K/s], \tag{XIX}$$

where: Λ_t – total thermal diffusivity, [1/s]; A – area of the construction, [m^2]; $\Delta\Theta$ – temperature difference between outside and inside, [K].

2.6. Time step and its influence to the Fourier number

As mentioned in previous chapters, Fourier number describes the accuracy of calculation of the unsteady heat transfer. The expression of Fourier number (IV) shows, that choice of this number is relevant to time step Δt and layer's thickness Δx. In this chapter it is discussed more detailed about time step's detection method and dependence of the Fourier number.

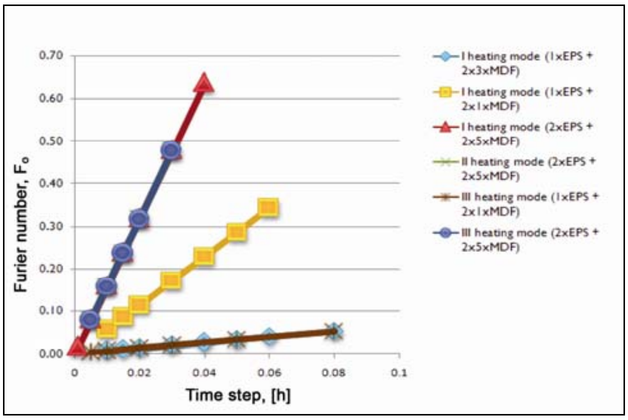

Fig. 9. Dependence of the Fourier number to time step *Δt*

Fig. 9 shows the variation of the Fourier number when time step Δt is changing. Simulation of all heating modes showed, that the most detailed fragmentation variants (2xEPS, 5xMDF) demand smaller time step in order to maintain the proper Fourier number.

Dividing materials in conditional layers with the same thermal diffusion the idea is maintained that the Fourier number of all materials must be equal (He *et al.* 2004; Hence *et al.* 2001). According to formulas (IV, XV) the time step may be expressed:

$$\Delta t = \frac{F_o}{\Lambda} = F_o \cdot \tau_{sl}, [s], \tag{XX}$$

where: Δt – time step, [s]; F_o – Fourier number; Λ – thermal diffusion, [1/s]; τ_{sl} – time constant of the layer, [s].

Formula (XX) may be used for calculation of time step, but at first it is needed to know suitable Fourier number.

2.7. Cooling (heating) speed and acceleration

Expressions of cooling (heating) speed and acceleration are based on the basic kinematics equations. Cooling (heating) speed is defined as temperature difference during the period of time (XXI). Cooling (heating) speed's unit of measurement is degrees per second [°C/s]. Cooling (heating) acceleration is defined as a speed difference of cooling (heating) during the period of time (XXII). Acceleration unit of measurement is degrees per squared second [°C/s^2]. For convenience, better choice of measurement units is degrees per hour – [°C/h] and degrees per squared hour– [°C/h^2].

$$\upsilon = \frac{\Delta\Theta}{\Delta t} = \frac{\Theta - \Theta_o}{\Delta t}, [{}^oC/h], \tag{XXI}$$

where: $\Delta\Theta$ – temperature difference during the period of time, [°C]; Θ_o – temperature at starting point, [°C]; Θ – temperature at final point, [°C]; Δt –time step, [h].

$$a_\upsilon = \frac{\Delta\upsilon}{\Delta t} = \frac{\upsilon - \upsilon_o}{\Delta t}, [{}^oC/h^2], \tag{XXII}$$

where: $\Delta\upsilon$ – speed difference of cooling (heating), [°C]; υ_o – speed at starting point of cooling (heating), [°C]; υ – speed at final point of cooling (heating), [°C]; Δt – time step, [h].

Our researches showed that the cooling (heating) speed and acceleration have exclusive importance to the accuracy of calculation of the unsteady heat transfer. The graphs (Figs. 10, 11 and 12) show the accuracy of calculating, which is expressed by the difference of calculated and measured values of the temperature. In the same graphs the variation of cooling (heating) speed and acceleration in time is also presented. It should be noted, that analyzing the third heating mode, when $F_o = 0.03$, what should dictate a good accuracy of calculation, the difference between calculated and measured values is sufficiently high. The reasons for this law are linked to the cooling (heating) speed and acceleration values, which increase to 9°C/h and more (Fig. 10).

Fig. 11 and Fig. 12 show the same tendencies like Fig. 10. The variation of cooling (heating) speed affects larger difference between calculated and measured values which means smaller accuracy of calculation.

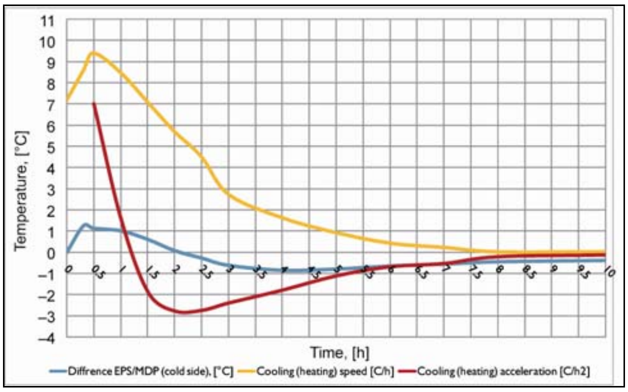

Fig. 10. The dependence of cooling (heating) speed and acceleration on accuracy of calculation in time, when Δt = 0.01 h, F_o= 0.03, III heating mode, 2xEPS (25.3 mm) + 5xMDF (5 mm)

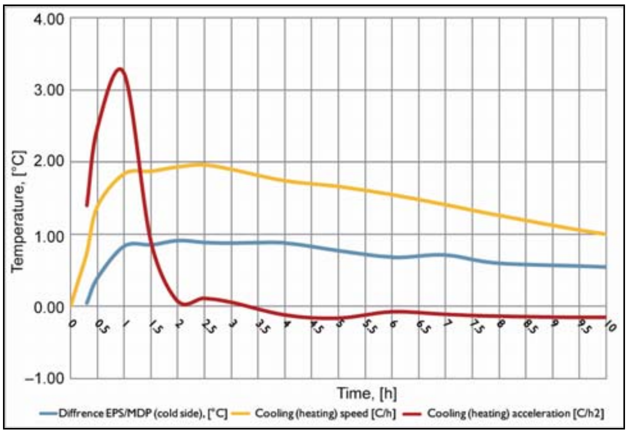

Fig. 11. The dependence of cooling (heating) speed and acceleration on accuracy of calculation in time, when Δt = 0,03 h, F_o= 0.48, III heating mode, 2xEPS (25.3 mm) + 5xMDF (5 mm)

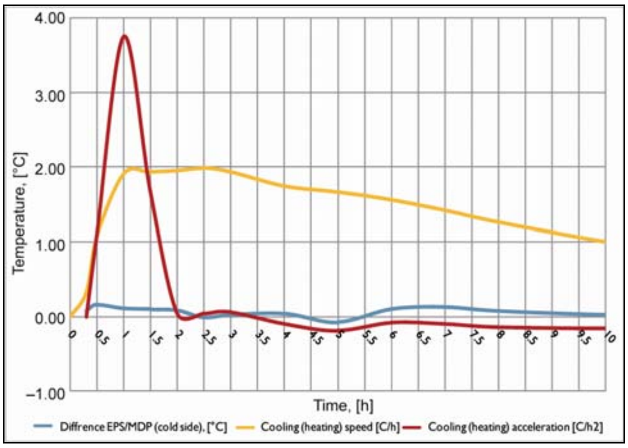

Fig. 12. The dependence of cooling (heating) speed and acceleration on accuracy of calculation in time, when Δt = 0,01 h, F_o= 0.02, III heating mode, 2xEPS (25.3 mm) + 5xMDF (5 mm)

3. Comparisons of research results

The accuracy of calculation and relevant choice of calculation parameters are estimated by comparing the results of experimental research with calculated ones. To achieve this purpose, results of experimental research were loaded into the spreadsheet and compared with calculated values of the temperature. The result of comparison is expressed as the difference between the calculated and measured values of the temperature.

The dependence of the Fourier number to the accuracy of calculation is showed in Fig. 13. It is presented graphically as the difference of measured and calculated values after 1,5 hours. All six curves define the results of each heating mode. The results of the first and the second heating modes have a lot of similarities, except the third heating mode. The third heating mode characterizes larger differences between the calculated and measured values after 1,5 h than the first or the second heating modes. Example of low accuracy is especially significant in the third heating mode where the construction is divided into conditional layers of 2xEPS and 5xMDF. Summarizing the results of Fig. 13 it can be concluded that the Fourier number indicates the tendencies of accuracy of calculation of the unsteady heat transfer.

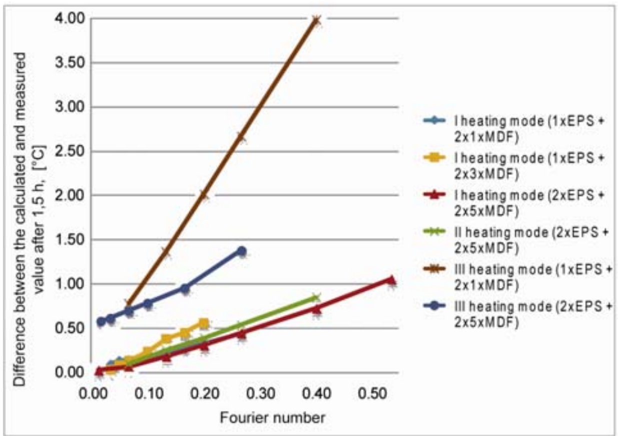

Fig. 13. The dependence of the Fourier number on accuracy of calculation after 1.5 h

Fig. 14 shows the dependence of the Fourier number on accuracy of calculation after 5 hours. In Fig. 14 it is needed to distinguish curves of the third heating mode, which are decreasing due to the increasing Fourier number. This phenomenon may be defined as the sequence of the oscillation. That means the calculated value is oscillating around the real value. Oscillation exists in all cases of calculation, but when Fourier numbers are low (F_o= from 0 to 0.5) the oscillation amplitudes are disappearing.

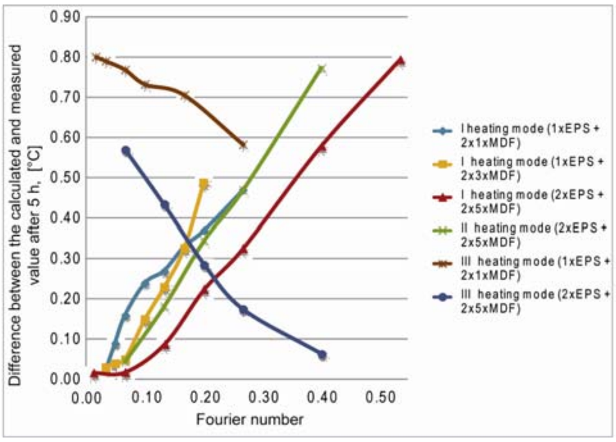

Fig. 14. The dependence of the Fourier number on accuracy of calculation after 5 h

4. Conclusions

1. Calculating temperatures in unsteady heat transfer case, it is recommended to divide the materials of construction into conditional layers of equal thermal diffusion.

2. Our researches showed that the parameters of cooling (heating) speed and acceleration have a significant influence on accuracy of calculation of the unsteady heat transfer. Regardless, if the value of Fourier number is low ($F_o = 0.05 – 0.1$), but the cooling (heating) speed and acceleration are large, the accuracy of calculation may be poor.

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FURJĖ KRITERIJAUS ĮTAKA PASTATO ATITVARŲ NESTACIONARIŲJŲ ŠILUMOS MAINŲ SKAIČIAVIMUI

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S a n t r a u k a

Pasikeitus temperatūrai bet kurioje atitvaros pusėse, pasikeičia ir šilumos srautas, sklindantis per atitvarą, kuris kinta tol, kol tampa nuolatinis (stacionarus), atsiranda šiluminė pusiausvyra. Realiomis sąlygomis šilumos mainai pastatuose vyksta nestacionarios būklės, t. y. kinta laiko atžvilgiu. Šiluminių mainų procesų nepastovumas atsiranda svyruojant lauko oro temperatūrai, išsiskiriant šilumos pritekėjimams pastate, veikiant saulės spinduliuotei ar kitiems veiksniams, kurie daro įtaką šiluminiam visą pastato balansui. Skaičiuojant nestacionariuosius šilumos mainus, svarbu tinkamai sudalinti medžiagą reikiamu sluoksnelių skaičiumi. Sluoksnelis – tai medžiagos storis, kuriame menamai vyksta stacionarus šilumos perdavimas. Laiko žingsnis, kuriuo temperatūra šuoliuoja per sluoksnelius, ir temperatūrinis laidis, kuris išreiškia temperatūros suvienodėjimo spartą, tai dar du parametrai, darantys poveikį skaičiavimo tikslumui. Visų šių parametrų derinys išreiškiamas Furjė kriterijumi.

Atlikti tyrimai parodė, kad sluoksnelius racionalu sudalinti vienodomis temperatūrinėmis pralaidomis, o sluoksnelių aušimo (šilimo) greičio ir pagreičio vertės daro svarią įtaką skaičiavimo tikslumui.

Reikšminiai žodžiai: nestacionarus šilumos perdavimas, Furjė kriterijus, aušimo (šilimo) greitis, aušimo (šilimo) pagreitis, sąlyginis sluoksnio storis, temperatūrinė pralaida, karšta dėžė.

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