ISSN 2029–9990 JOURNAL OF SUSTAINABLE ARCHITECTURE AND CIVIL ENGINEERING 2013. No. 1(2)
DARNIOJI ARCHITEKTŪRA IR STATYBA

Investigation into Thermal Capacitance of the Building Envelope

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crossref http://dx.doi.org/10.5755/j01.sace.1.2.3543

The purpose of this research is to determine the actual effective thermal capacitance of the building envelope in respect of the place of thermal layer in the enclosure. The actual effective thermal capacitance of the building envelope is estimated by calculating the thermal capacitance of building enclosure layers in order to find out the active thermal capacitance of the enclosure. This research analyses unsteady heat transfer cases. The calculation principle of such transfers is based on the finite elements method. The specific value of the Fourier number, which gives calculations the optimal accuracy, is determined. This paper also discusses three types of envelope constructions. In all three cases, thermal resistance of the envelopes coincides; only the position of thermal insulation layer in the envelopes is different. In all three cases, time delay of the indoor air temperature in respect of the outdoor air temperature, as well as decrement factors of the oscillation amplitude are calculated. These factors of inertia were determined at the continuous outdoor air temperature oscillation. The research revealed that continuous outdoor air temperature oscillations through multi-layered building enclosures are suppressed by high thermal capacitance enclosure layers, independently from their position. High thermal capacitance enclosure layers oriented to the interior of the premises suppress the fluctuations more efficiently than those oriented to the exterior.

Keywords: *building envelope, enclosure, time constant, Fourier number, thermal capacitance, time delay, decrement factor.*

1. Introduction

When analysing unsteady thermal processes in buildings and classifying the buildings according to their thermal inertia factors, it is important to properly evaluate the influence of building enclosures on the internal temperature fluctuation due to the outdoor temperature changes. The effective thermal capacitance C_{eff} of the building envelope, thermal time constant τ and actual thermal delay are the indicators of the thermal inertia of the building. Therefore, it is important to evaluate them appropriately.

The methodology of the Lithuanian Standards Board (LST EN ISO 13790:2008) classifies buildings into inertia classes according to the value of time constant. Thermal time constant of the building τ is expressed as a proportion between the internal active thermal capacitance of the building C_m and heat transfer coefficient of the building H (LST EN ISO 13790:2008):

$$\tau = \frac{C_m / 3600}{H_T + H_V}, (h) \tag{1}$$

where: C_m – internal active thermal capacitance, J/K; H_T – heat transfer coefficient of building enclosures, W/K; H_V – ventilation heat loss coefficient, W/K.

The average active thermal capacitance C_m is defined as the heat accumulated inside the building, when the internal air temperature oscillates according to the sinusoid with the period t-24h and the amplitude 1K (LST EN ISO 13790:2008).

The value of the internal thermal capacitance of the building depends on the amplitude of temperature oscillation in the premises; the allowed fluctuation limits depend on the purpose of the premises (Šeduikytė et al. 2008, LST EN ISO 7730, STR 2.09.02:2005).

The standard (LST EN ISO 13790:2008) evaluates active thermal capacitance C_m only inside the building, i.e. it evaluates energy costs per year when temperature fluctuations occur inside the building, which is not a very accurate method for evaluating the complex influence of the building envelope on the thermal regime of the premises and selecting the capacity of the heating system. Continuous fluctuations of the outdoor air temperature affect the building enclosures first, and only then these fluctuations make an impact on the thermal regime of the premises.

Swedish scientists Adamsson, Dafgard, Rydberg and Peterson (Berg-Hallberg 1985) were among the first to classify buildings according to the value of time constant.

When classifying buildings, the scientists evaluated the thermal capacitance of the building envelope taking into account all the layers of the enclosure, or half of the thermal capacitance of the enclosure, or the internal layers of the enclosure up to thermal insulation layer.

According to (Kalema et al. 2006), the thermal capacitance of the construction taken into account is limited to 0.10 m from the surface, or to the first insulation layer.

When classifying buildings according to the time constant factor, Antonopoulos et al. (1995) calculate thermal capacitance using the lump capacitance method:

$$C = \sum v_n \rho_n c_n, (J/K) \tag{2}$$

where: v_n, ρ_n and c_n are the volume, density and specific heat, respectively, of element n.

Thermal regime inside the building is affected in two ways: due to infiltration and through the external building envelope. In reality, most of the buildings are made of enclosures of different construction types, depending on the purpose and technological regime of the building and dominant construction traditions in the country. The massive layer of multi-layered enclosures can be oriented to the exterior or the interior of the building, or it can be in the middle of the enclosure. Thermal capacitance is an important quality that enables walls to absorb, store and later release thermal energy into the building space.

The aim of this work is to determine the effect of massive layer position in the enclosure on the thermal inertia of the enclosure.

2. Methods

The accuracy of calculations of unsteady heat transfer using the finite elements method depends on the selected values of Fourier and Biot numbers.

The Fourier number is designated by the symbol F_o and the equation for every layer of this number is (Stankevičius et al. 2000, Incropera et al. 2007, Hagentoft 2001):

$$F_o = \frac{a \cdot \Delta z}{d^2} \tag{3}$$

The Fourier number can also be expressed as:

$$F_o = \frac{\lambda \cdot \Delta z}{\rho \cdot c_p \cdot d^2} = \frac{\Delta z}{C_{sl} \cdot R_{sl}} = \frac{\Lambda_{sl} \cdot \Delta z}{C_{sl}} = A \cdot \Delta z; \tag{4}$$

where: a – the thermal diffusivity, (m²/s); Δz – the time step, (s); d – thickness of conditional layer, (m); λ – thermal conductivity, (W/(m×K)); ρ – material density, (kg/m³); c – specific thermal capacity , (J/(kg×K)).

The thermal capacitance of the layer:

$$C_{sl.} = \rho \cdot c_p \cdot d, J/(m^2 \cdot K) \tag{5}$$

where: ρ – material density, (kg/m³); c – specific thermal capacity , (J/(kg×K)); d – thickness of layer, (m).

The thermal resistance of the layer:

$$R_{sl.} = d/\lambda, (m^2 \cdot K)/W \tag{6}$$

where: d – thickness of material, (m); λ – thermal conductivity, (W/(m×K).

The thermal diffusion of the layer (Pupeikis *et al.* 2010):

$$\Lambda_{sl.} = \lambda / d, \ W/(m^2 \cdot K) \tag{7}$$

where: ᴧ – thermal conductance, (W/m²×K); λ – thermal conductivity, (W/(m×K)); d – thickness of layer, (m).

The thermal diffusivity of the material:

$$a = \frac{\lambda}{\rho \cdot c_p}; m^2/s \tag{8}$$

where: λ – thermal conductivity, (W/(m×K)); ρ – material density, (kg/m³); c – specific thermal capacity , (J/(kg×K)).

The thermal diffusion of the separate layer:

$$A_{sl} = \frac{a}{d^2}, (1/s) \tag{9}$$

where: A_{sl} – thermal diffusion of the material layer [1/s]; a – thermal diffusivity of material, [m²/s]; d – thickness of layer, [m].

The dependence of layer thickness on the Fourier number and time step:

$$d = \sqrt{\frac{a \cdot \Delta z}{F_o}}, (m) \tag{10}$$

where: a – thermal diffusivity of material, (m²/s); d – thickness of layer, (m); Δz – the time step, (s); F_o – Fourier number.

Thermal diffusivity of the material a (m²/s; m²/h) shows the rate of temperature “diffusion/equalization” in the object, i.e. the part of 1 m distance per time unit for the temperature to equalize in the homogeneous object from the initial moment, when the temperature drop between two planes (points) at 1 m distance is 1K.

The inverse proportion 1/a (s/m²; h/m²) shows the time in which the temperature equalizes between two planes (points) of the homogeneous object at 1 m distance, when the temperature drop at the initial moment is 1K. Suppose, there is an EPS with the following characteristics: $\lambda = 0{,}07$ W/(m×K); $\rho = 25$ kg/m³; $c_p = 1340$ J/(kg×K), then, the calculations are performed according to (8) $a = 0{,}00000209$ m²/s ≈ 0,0075m²/h and 1/a = 478571 s/m² ≈ 133 h/m².

Thermal diffusion of the layer A (1/s; 1/h) shows the rate of thermal “diffusion/equalization”, i.e., the part of layer thickness Y per time unit for the temperature to equalize in the homogeneous object from the initial moment, when the temperature drop on both sides of the layer is 1K.

The inverse proportion *1/A* (s; h) shows the time in which the temperature equalizes in the homogeneous layer, when layer thickness is Y and temperature drop in the layer at the initial moment is 1K.

Suppose, there is an EPS layer with the following characteristics: λ = 0,07 W/(m×K); $\rho = 25$ kg/m³; $c_p = 1340$ J/(kg×K), $d = 50$mm, then, the calculations are performed according to (9): $A \approx 3{,}01$,(1/h) and 1/$A \approx 0{,}332$, (h).

Fourier number F_o – shows the thickness (depth) of "equalization" in the layer during the selected time step Δz, i.e., the part of layer thickness Y for the temperature to equalize in the homogeneous layer from the initial moment during the time period Δz, when the temperature drop on both sides of the layer, whose thickness is Y, is 1K.

The inverse proportion $1/F_o$ – shows how much more time it would take, in comparison to the time period Δz, for temperature to equalize in the whole homogeneous layer, when the thickness of the layer is Y, and the temperature drop in the layer at the initial moment is 1K. Suppose, there is an EPS layer with the following characteristics: $\lambda = 0{,}07$ W/(m×K); $\rho = 25$ kg/m^3; $c_p = 1340$ J/(kg×K), $d = 50$mm, $\Delta z = 0{,}1$ h, then, the calculations are performed according to (4): $F_o \approx 0{,}301$ and $1/F_o \approx 3{,}322$.

Thus, if $\Delta z = 0{,}1 \times 3{,}322 \approx 0{,}3322$ h, then $F_o \approx 0{,}9999$ and $1/F_o \approx 1{,}000$; in other words, during this time period, the temperature equalizes in all the thickness of the layer.

$$F_o = A \cdot \Delta z = \frac{\lambda \cdot \Delta z}{c_p \cdot \rho \cdot d^2} \tag{11}$$

The Biot number is usually expressed as:

$$Bi = \frac{h \cdot d}{\lambda} \tag{12}$$

where: h – surface heat exchange coefficient, d – thickness of the surface layer of the enclosure, λ – thermal conductivity coefficient of the surface layer of the material.

The Biot number can also be expressed in the following way:

$$Bi = h_{pav.} \cdot \Delta R_{pav.sl.} = \frac{h_{pav.}}{\Lambda_{pav.sl.}} = \frac{\Delta R_{pav.sl.}}{1/h_{pav.}} \tag{13}$$

where: $h_{pav.}$ – surface heat exchange coefficient; $\Delta R_{pav.sl.}$ – thermal resistance of the first surface layer; $\Lambda_{pav.sl.}$ – thermal diffusion of the first surface layer (the inverse proportion of thermal resistance).

According to (Karbauskaite et al. 2008, Hensen 1994), the limit value of the Fourier number is equal to 0.5. The values of this number are higher than 0.5 and cause significant errors in temperature calculations. In some cases, the temperature calculation average error increases significantly when the value of the Fourier number reaches 0.47 (Pupeikis *et al.* 2012).

In case of transient heat transfer, the temperature in any plane of enclosure is determined by the following equation (14) in (Fig. 1):

$$\Theta'_n = \Theta_n + \left(\frac{\Theta_{n-1} - \Theta_n}{\Delta R_{n-1}} - \frac{\Theta_n - \Theta_{n+1}}{\Delta R_n} \right) \cdot \frac{2 \cdot \Delta z}{d_{n-1} \cdot c_{n-1} \cdot \rho_{n-1} + d_n \cdot c_n \cdot \rho_n} \tag{14}$$

It is understood as (15) or (16),

$$\Theta'_n = \Theta_n + \left(q_{n/(n-1)'} - q_{(n+1)/n} \right) \cdot \frac{2 \cdot \Delta z}{\chi_{n-1} + \chi_n} \tag{15}$$

or

$$\Theta'_n = \Theta_n + \left(q_{n/(n-1)'} - q_{(n+1)/n} \right) \cdot \frac{1}{s_{(n+1)(n-1)}} = \Theta_n + \frac{\Delta q'_{(n+1)(n-1)}}{s_{(n+1)/(n-1)}} = \Theta_n + \Delta t'_{n/n'} \tag{16}$$

where: Θ'_n – temperature of plane n at the present time moment; Δz – time period (calculation time step), (s); d_n – thickness of layer between "n" and "$n+1$" planes, (m); c_n – specific thermal capacity of layer between "n" and "$n+1$" planes, (J/(kg·K)); ρ_n – the material of layer between "n" and "$n+1$" planes density, kg/m^3; $q'_{n'/(n-1)}$ – the potential of heat flow density between "n" and "$n-1$" planes at the time moment after time period Δz, (W/m^2); $q'_{(n+1)/n'}$ – heat flow density between "n" and "$n+1$" planes at the initial time moment z, i.e. the heat flow rate due to temperature difference ($\Theta_n - \Theta_{n+1}$), W/ m^2; χ_{n-1} ir χ_n – coefficient of area thermal capacitance of the layer "$n-1$" and "n", (J/(m^2×K)); $S_{(n+1)/(n-1)}$ – the average thermal receptivity of the material of both layers "$(n-1)$" and "n", (W/(m^2×K)); $\Delta t_{n/n'}$ – temperature change in the plane "n" after the time period Δz passed from the initial time moment.

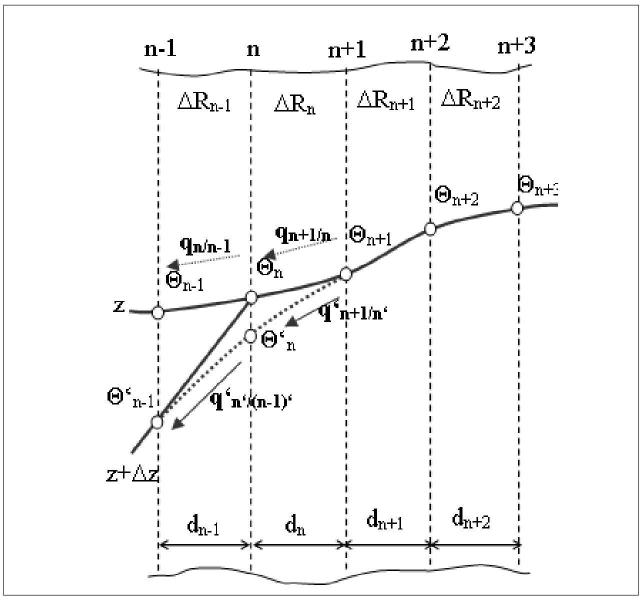


Fig. 1. *Principle scheme for calculating the interlayer temperature of the enclosure*

According to (Incropera et al. 2007), it is recommended that the first surface layer thickness amounted to ½ of the thickness of other layers, since it is important for obtaining the required Biot number. For the calculation of a unidimensional temperature field, when F_o is inside the enclosure, the stability criteria is the following: $(1-2 \cdot F_o) \geq 0$, from here $F_o \leq 0{,}5$;

When Bi is displayed on the surface of the wall, the stability criteria is the following: $(1 - 2 \cdot F_o - 2 \cdot Bi \cdot F_o) \geq 0$, from here $F_o \cdot (1+Bi) \leq 0{,}5$.

The second criterion with Bi is more sensitive than the first one; therefore, it has to be used for determining the critical (the largest allowed) calculation time step Δz:

The positive $Bi \leq 0,1$ is preferred.

The maximum allowed F_o is determined applying:

$$F_o \leq \frac{0,5}{1+Bi} \quad (17)$$

Using the maximum allowed F_o, the maximum allowed time step is calculated:

$$\Delta z \leq \frac{F_o \cdot d^2}{a} \quad (18)$$

The finite elements difference explicit method is used for calculating new values using the already know ones.

3. Materials and equipment

Two building models were made for the experiments. Heat transfer coefficient of the internal surface of the enclosures of models WM-I and WM-II, which describes the surface heat exchange of the enclosure with the environment, is the following:

$$h_s = Nu \cdot \left(\frac{\lambda}{s}\right) + \frac{4 \cdot \sigma \cdot \left(\frac{T_s + T_{air}}{2}\right)^3}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}, (W/m^2K) \quad (19)$$

where: $\sigma = 5.6704 \cdot 10^{-8}$ – Stefan–Boltzmann constant, ($W \times m^{-2} \times K^{-4}$); s – thickness of air boundary layer, (m); Nu – Nusselt number calculated according to LST EN 673:2011; λ – thermal conductivity of still air, W/(m·K); T_s – temperature of the surface, (K); T_{air} – surround air temperature, (K); ε_1 – emissivity of surface; ε_2 – emissivity of surrounding.

The measured thermal properties of materials used in wall models WM-I and WM-II are presented in (table 1). The thermal conductivity values of the materials were measured according to (LST EN 12667:2002, Stankevičius et al. 2005) in lambda apparatus which meets the requirements of (ISO 8301:1991). The density of materials was determined in accordance with (LST EN 1602: 1998, LST EN 1602: 1998/AC:2003).

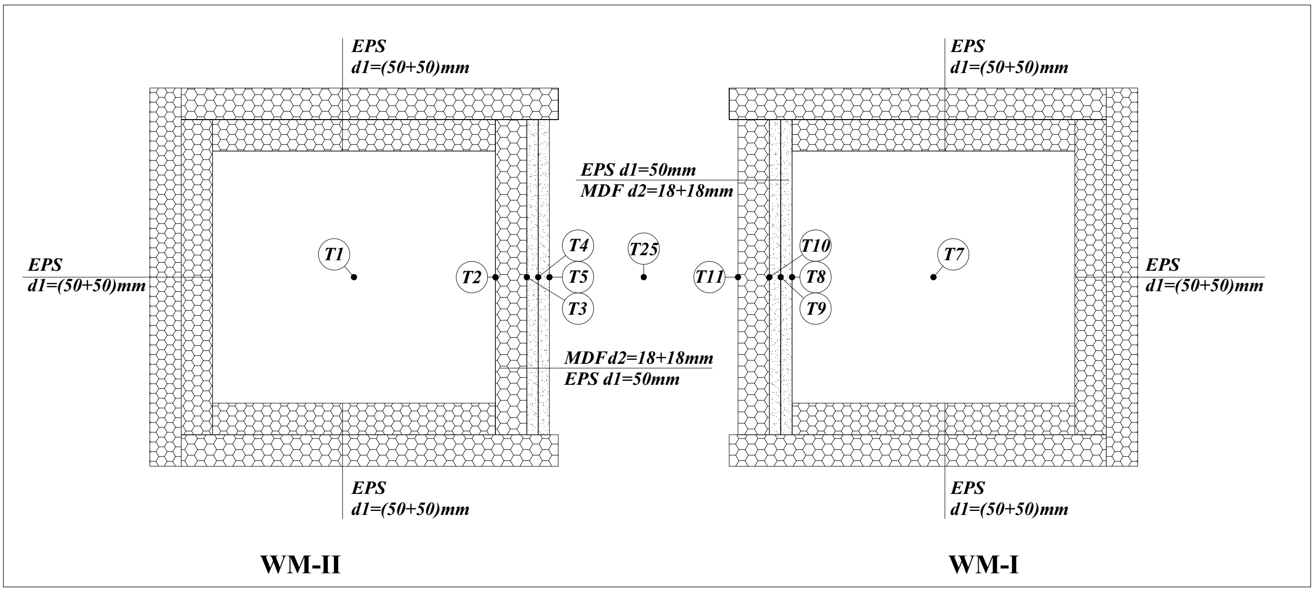


Fig. 2. *Structural scheme of thermocouple arrangement and models. T- thermocouples*

Table 1. *The walls studied: WM-I and WM-II with the same values of thermal transmittance U, but with different values of internal areal thermal capacity*

Walls model	**WM-I**	**WM-II**
Thickness, (mm)	50.0 + 36.0 = 86.0	36.0 + 50.0 = 86.0
Insulation (EPS - expanded polystyrene)		
Conductivity λ, (W/m·K)	0.039	0,039
Density ρ, (kg/m³)	15.807	15.807
Thermal capacity c, (J/kg·K)	1450	1450
Mass (MDF – medium density wood fibreboard)		
Conductivity λ, (W/m·K)	0.12	0.12
Density ρ, (kg/m³)	787.22	787.22
Thermal capacity c, (J/kg·K)	1430	1430
Thermal transmittance U_{wall}, ($W/(m^2 \cdot K)$)	0.57	0.57

The thermal capacitance values of common construction materials used in the experiment were selected from literature sources in accordance to the type and density of the materials. Both models WM-I and WM-II were made of materials commonly used in practice (Fig. 2). Five walls of the model 600 x 600 x 600 mm (length x width x height) were made of polystyrene (EPS) boards $d_1 = 50 + 50$ mm. Heterogeneous enclosure of the models consists of two medium density wood fibre boards (MDF), with the thickness of $d_2 = 18 + 18$ mm, and one expanded polystyrene (EPS) board, $d_1 = 50$mm.

Internal and external volumes of the models are identical, but the position of MDF massive layer in heterogeneous enclosures is different: in WM-I, it is oriented to the interior, and in WM-II, it is oriented to the exterior.

4. Experimental and results

In order to determine the accuracy of the calculation method, the experiment was carried out. On the basis of the experiment, the calculation program was created for the evaluation of unsteady heat exchange in multi-layered enclosures (using MS Excel). In conditional layers of the enclosure, temperature fluctuations are calculated using finite elements method, and the values of internal enclosure layers are estimated according to the equations given in Chapter 2.

The experiment was carried out by imitating climatic conditions in the climatic test chamber, in the Laboratory of Building Thermal Physics at Institute of Architecture and Construction of Kaunas University of Technology, (KTU ASI). Two spatial models, differing in the position of their high thermal resistance layer, i.e. inside and outside of the model, were constructed in the chamber. The aim of the experiment was to change the temperature of the surroundings by cooling and heating it and observe temperature changes in the walls and the interior of the models. In order to ensure the accuracy of the experiment, the values of thermal parameters of the materials were determined and the thermocouples measuring the temperature were calibrated.

During the experiment, the temperature was measured every one second and the average of one minute was recorded (one minute time step is also acceptable in calculations). Data accumulator DL-3 scanned the values of automatically measured temperatures, recorded them and presented in MS Excel format.

During the experiment, the dynamic temperature oscillation consisting of seven cooling and heating cycles was created in the climatic chamber using cooling and heating devices. Before the experiment, steady temperature of $\Theta_i = +18.56$ ºC was settled in the climatic chamber and inside the models WM-I and WM-II. Dispersion limits of the thermocouples (T1...T25) were the following: $A_e = \pm 0.25$ ºC.

The experiment begins with the cooling cycle, which lasts for three hours. The temperature inside the climatic chamber is lowered down to $\Theta_e = (-20)$ ºC. When this cycle is over, a two-hour heating cycle begins and the temperature raises up to $\Theta_e = (+25)$ ºC. The temperature oscillation amplitude is equal to $A_e = (+25$ ºC$)\div(-20$ ºC$)$.

Using the outdoor air temperature oscillation data obtained during the experiment, calculations were performed in order to determine the temperature of the indoor air and wall interlayers. The temperatures were compared with the values measured during the experiment.

The accuracy of the calculations in the non-homogeneous (multi-layered) enclosure depends on the Fourier number, which defines the conditions of gradual change and the selection of the rational number of conditional layers. When there is a significant difference among the Fourier number values of different layers in multi-layered enclosure $F_{oMDF} = 0.710$ and $F_{oEPS} = 0.398$, the temperature distribution dotted curve obtained using the calculation program does not correlate with the experimental data bolded solid curve (Fig. 3).

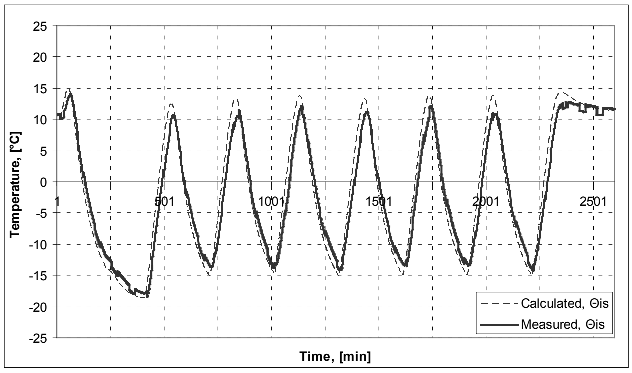


Fig. 3. *Correlation of experimental temperature value of the internal surface of multi-layered enclosures of WM-I model with temperature values obtained using the calculation program, when* $F_{oMDF} = 0.710$; $F_{oEPS} = 0.398$

Thus, the experiment clearly shows that the least distorted calculation results were obtained when the layers of multi-layered enclosure made of different materials were divided into rational layers so the values of the Fourier number were closely equal. In case of the experimental calculation, the values were $F_{oMDF} = 0.177$ and $F_{oEPS} = 0.1633$. The dotted curve, representing the distribution of the temperature calculated using the calculation program, completely correlates with the bolded solid curve representing the experimental data in (Fig. 4).

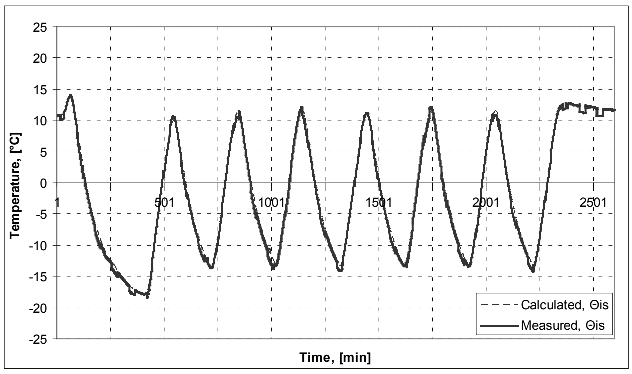


Fig. 4. *Correlation of experimental temperature value of the internal surface of multi-layered enclosures of WM-I model with temperature values obtained using the calculation program, when* $F_{oMDF} = 0.177$; $F_{oEPS} = 0.1633$

The calculation program is sufficiently accurate for carrying out further research.

5. The effect of wall's massive layer position on time delay, decrement factor and inside temperature

Time delay and decrement factor are very important factors for the evaluation of thermal resistance of the material. The outdoor air temperature changes chaotically during a 24-h period (Bruzgevičius *et al.* 2012) and influences the microclimate of the premises. Building enclosures work as a passive microclimate system and reduces the effect of the outdoor air temperature on the microclimate of the premises. The thermal inertia properties of the enclosures help to reduce energy consumption for ensuring microclimate comfort in the premises during the hot or cold season.

Many construction types of building enclosures are applied in practice. The outdoor air temperature wave diffuses through building envelope constructions with different time delay due to the inertia properties of the building envelope. The time delay of temperature fluctuation the premises caused by outdoor air temperature fluctuations depends on the thermal inertia of enclosures.

The temperature oscillation is assumed to show sinusoidal variations during a 24-h period. Time delay Φ is defined as (20):

$$\Phi_{\min} = \Theta_{\Theta i,\min} - \Theta_{\Theta e,\min} \quad (20)$$

$$\Phi_{\max} = \Theta_{\Theta i,\max} - \Theta_{\Theta e,\max} \quad (21)$$

The proportion of the amplitudes of the indoor and outdoor air temperature is called the wave decrement factor, which is expressed by the following equation (Cibse guide 1988, Kontoleon *et. al.* 2005) as (22):

$$f = \frac{A_i}{A_e} = \frac{\Theta_{i,\max} - \Theta_{i,\min}}{\Theta_{e,\max} - \Theta_{e,\min}} \quad (22)$$

where: A_e – amplitude of outdoor air temperature oscillation, (°C); A_i – amplitude of indoor air temperature oscillation, (°C); $\Theta_{e,max}$ – maximum outdoor air temperature, (°C); $\Theta_{e,min}$ – minimum outdoor air temperature, (°C); $\Theta_{i,max}$ – maximum indoor air temperature, (°C); $\Theta_{i,min}$ – minimum indoor air temperature, (°C).

These thermal inertia parameters are ilustrated in figure 5.

Under natural conditions, the outdoor air temperature is influenced by a number of factors: solar radiation, cloudiness, heat absorption and reflection of the ground surface, wind speed, atmospheric pressure and many other (Rimkus *et. al.* 2007). All these factors, their values and combinations influence the fluctuation of the outdoor air temperature. In this research, only the influence of the outdoor air temperature is analysed. In simple cases of the outdoor air temperature forecast, it is assumed that temperature oscillates regularly around its average value according to a cosinusoid. According to this method, the air temperature Θ_d after the time period t is expressed as (Phokin 2006):

$$\Theta_d = \Theta_a + A_e \cdot \cos\left(\frac{2\pi}{T} \cdot t\right),\ (^oC) \quad (23)$$

where: Θ_d – average outdoor temperature, (K); A_e – amplitude of outdoor temperature oscillation, (K); T – period of temperature oscillation, (h); t – time from the beginning of oscillation, (h).

6. Discussion and analysis

Three structural types of wall insulation have been taken for investigation of time delay and decrement factor (table 2). In wall WM-I the insulation is positioned outdoors; in WM-II the insulation is positioned indoors; the WM-III is a single-layer EPS insulation. In all three types wall the thermal transmittance is the same (U_{wall} = 0.57 W/(m²·K)). The temperature values inside these walls are calculated according to the equations given in Chapter 2.

The outdoor temperature oscillation curves, given in Fig. 6 are used for simulation of walls WM-I, WM-II and WM-III. Periods of outdoor temperature oscillation varies from 0.5 to 10 hours from (a) to (f) (Fig. 6).

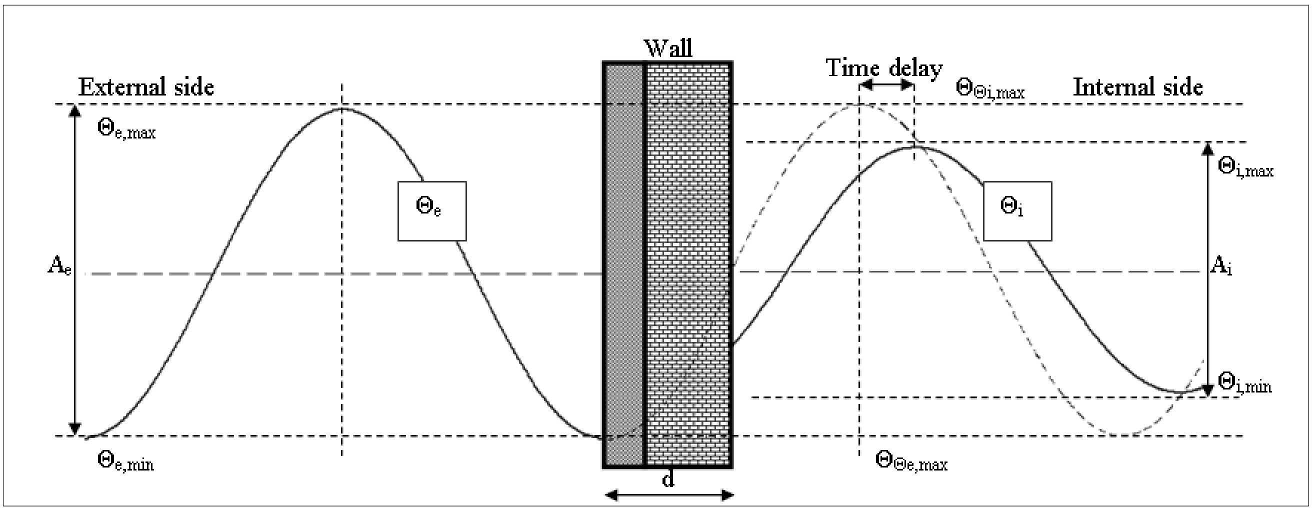
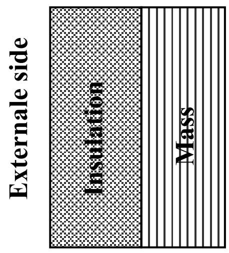
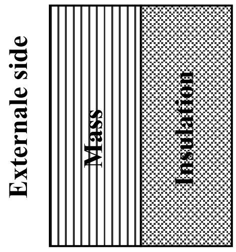
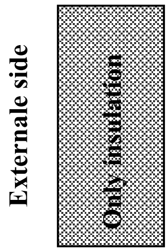


Fig. 5. *Scheme of time delay and decrement factor*

Table 2. *The walls studied: WM-I, WM-II, WM-III with the same values of thermal transmittance U*

Wall models	**WM-I**	**WM-II**	**WM-III**
			
Thickness, (mm)	50.0 + 36.0 = 86.0	36.0 + 50.0 = 86.0	61.7
Insulation (EPS - expanded polystyrene)			
Conductivity λ, (W/m·K)	0.039	0.039	0.039
Density ρ, (kg/m³)	15.807	15.807	15.807
Thermal capacity c, (J/kg·K)	1450	1450	1450
Mass (MDF – medium density wood fibreboard)			
Conductivity λ, (W/m·K)	0.12	0.12	–
Density ρ, (kg/m³)	787.22	787.22	–
Thermal capacity c, (J/kg·K)	1430	1430	–
Thermal transmittance U_{wall}, W/(m²·K)	0.57	0.57	0.57
Period of temperature oscillation	**Time delay, *φ*** (h)		
0,5	14	14	11
1	22	21	20
2	33	31	29
4	48	47	42
5	51	51	46
10	68	68	53
Period of temperature oscillation	**Decrement factor, *f*** (–)		
0,5	0.037	0.037	0.053
1	0.120	0.120	0.160
2	0.273	0.264	0.356
4	0.483	0.483	0.624
5	0.552	0.552	0.709
10	0.739	0.739	0.894

The massive (MDF – medium density wood fibreboard) materials are characterized by their capability to store energy in their thermal mass and cause a shift delay of temperature waves from outside to inside. This is caused by high thermal conductivity and volumetric thermal capacity of massive (MDF) materials. The due to their low thermal conductivity and volumetric thermal capacity, insulation materials respond like thermal barriers, significantly decreasing temperature fluctuations in the direction of the heat flow path.

Figure 7 shows the dependence of time delay and figure 8 shows the dependence of wave decrement factor of the enclosures WM-I, WM-II and WM-III on different oscillation periods of the outdoor air temperature (Fig. 6).

When the outdoor air temperature oscillation period is 0.5 h, the inertia of the enclosures WM-I and WM-II fully suppresses the outdoor air temperature oscillations on the inner surface, in comparison to the homogeneous EPS enclosure WM-III. When the oscillation period of the outdoor air temperature is 1 h, 2 h and 4 h, a 1 min difference in time delay values can be noticed due to different positions of the inertial massive layer in the enclosures. Time delay of fluctuations is more significant when the massive layer is oriented to the interior of the model WM-I. When the oscillation period of the outdoor air temperature is 5 h and 10 h, time delay values of the enclosures WM-I and WM-II become equal. During oscillation periods, the position of the inertial massive layer in the enclosure does not affect time delay.

Figure 8 shows decrement factor values of the enclosures WM-I, WM-II and WM-III. The closer are the decrement factor values to zero, the more inertial is the material. Comparing the values of wave decrement factor through each of three multi-layered enclosures, the inside surface temperature changes faster in model WM-III than in other models.

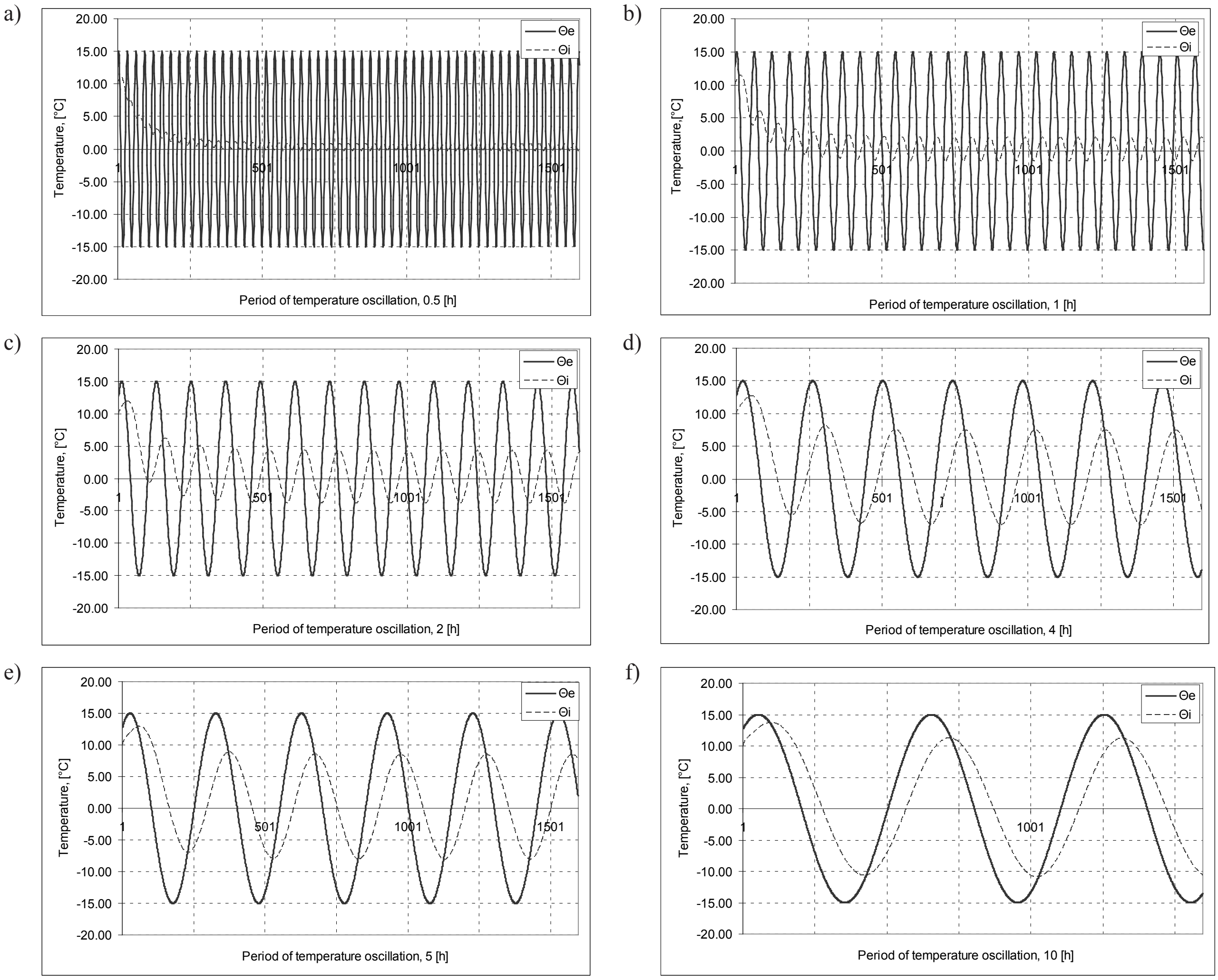


Fig. 6. *The impact of outdoor temperature oscillation to indoor temperature. Solid curve shows the exterior air Θ_e and the dotted curve shows the prognosticated internal air temperature Θ_i. Outdoor temperature curves are used for walls WM-I, WM-II, WM-III simulation. Periods of outdoor temperature oscillation varies from 0.5 to 10 hours. (Figures from (a) to (f))*

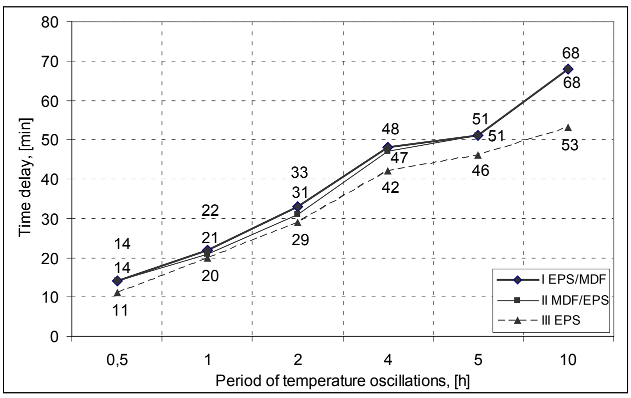


Fig. 7. *The time delay dependant on period of outdoor temperature oscillation*

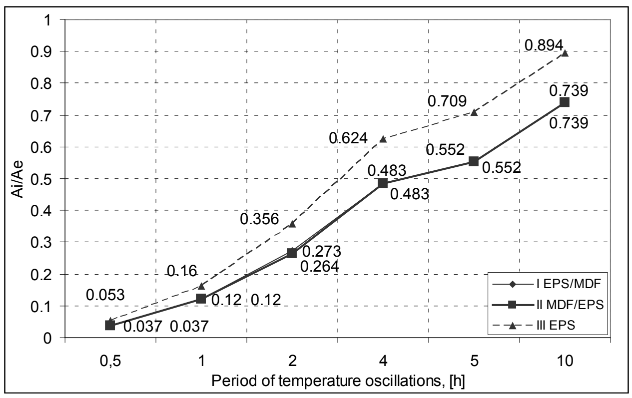


Fig. 8. *The decrement factor dependant on period of outdoor temperature oscillation*

7. Conclusions

1. Continuous outdoor air temperature fluctuations through multi-layered building enclosures were suppressed by high thermal capacitance layers of the enclosure, irrespective of their position. High thermal capacitance layers of enclosures oriented to the interior of the premises suppressed the fluctuations more effectively than the layers oriented to the exterior.

2. When classifying buildings according to their thermal inertia, thermal time constant should be calculated taking into account thermal capacitance of all the layers of building enclosures.

3. The least distorted calculation results were obtained when the multi-layered enclosure was divided into conditional layers so that their number values of the Fourier number were close to equal.

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Received 2013 02 20

Accepted after revision 2013 03 05

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