ASSESSMENT OF HEAT-STORAGE PROPERTIES OF BUILDINGS CONSTRUCTIONS BY USING COMSOL MULTIPHYSICS

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Abstract

The paper deals with testing of heat-storage properties in the building constructions by computer simulation. It describes the possibilities to determine the thermal stability and heat loss of the room during its cyclic heating and cooling with Comsol Multiphysics. The heat flux values obtained by computer simulation in the the tested room model were compared with the data acquired by real measurement with subsequent theoretical calculations carried out in accordance with the recommendations of the applicable Czech Technical Standards.

Data acquired by computer simulation enable to determine time constant for cooling of the tested room model.

1 Introduction

The continuous increase in the price of energy investments forces owners and users of all types of building structures to evaluate and optimize their operations. These requirements and relevant legislation lead to creation of new buildings designs and harmonization of their systems [1]. In building industry and architecture is currently used primarily software implementing only partial calculations related to the assessment of energy consumption of buildings. Therefore, we are dealing with the possibility to use modern software tools for comprehensive assessment of thermal stability and energy efficiency in buildings [2]. In this context, we test the software Comsol Multiphysics, which is designed to solve multiphysics problems. In the following text we describe the results obtained by testing of heat loss and thermal stability of the room model during the cyclic heating and cooling. We also describe comparison of the results obtained by computer simulation with real measured data and with data obtained by partial theoretical calculations according to recommended Czech Technical Standards.

2 Methods used for determination of thermal accumulation parameters

Two methods were compared by testing the heat losses of the room. The first method consisted in a computer simulation of non-stationary heat transfer in the assembled simplified model of the tested room under the required initial and boundary conditions, which corresponds to the conditions of the real experiment. The second method consisted of experimentally determining of the temperature distribution in the tested room during the cyclical heating and cooling for 9 days. Based on the results of the measurements, theoretical calculation of heat flux through outside wall of the room was performed in accordance with the Czech Technical Standards CSN EN 15251 and CSN 06220 [2], [3].

Comsol Multiphysics uses for numerical calculation of the non-stationary heat transfer the balance equation (Eq. (1)) [4]:

$$\rho \cdot c_p \frac{\partial T}{\partial t} + \rho \cdot c_p \cdot u \cdot \nabla T = (\lambda \nabla T) + \Phi_S, \tag{1}$$

ρ - density, [kgm^{-3}];
c_p - heat capacity at constant pressure, [Jkg^{-1}K^{-1}];
λ - thermal conductivity, [Wm^{-1}K^{-1}];
u - fluid velocity, [ms^{-1}];
Φ_S - heat capacity at constant pressure, [W];
T - temperature, [K];
t - time, [s].

For the theoretical calculation of the heat flux through the wall of room according the CSN 06 0220 it holds Eq. (2) [5]:

$$\Phi = AU\left(\theta_i\left(t\right) - \theta_e\left(t\right)\right), \tag{2}$$

A - heat transfer surface, [m^2];
U - heat passage coefficient, [Wm^{-2}K^{-1}];
θ_i - temperature of air inside the room, [°C];
θ_e - temperature of external air, [°C];
t - time, [s].

The heat passage coefficient (U) through the multilayer wall of the room can be calculeted according to Eq. (3) [5]:

$$U = \frac{1}{\frac{1}{h_i} + \frac{1}{h_e} + \sum_{j=1}^{n} \frac{\delta_j}{\lambda_j}}, \tag{3}$$

h_i - heat transfer coefficient of the inner wall surface, [Wm^{-2}K^{-1}];
h_e - heat transfer coefficient of the outside wall surface, [Wm^{-2}K^{-1}];
δ_j - thickness of the layer, [m];
λ_j - thermal conductivity of the layer, [Wm^{-1}K^{-1}];
n - number of the layers, [$-$];
j - layer number, [$-$].

For a theoretical calculation we determined the outside air temperature as daily mean air temperature calculated from measured values of the outside air temperature in a given timeframe.To assess the energy performance of buildings is recommended according to Czech Technical Standard CSN EN 15251 to determine the temperature of the outside air as a running mean external temperature (Eq. (4)) [3]:

$$\theta_{rm} = (1-\alpha)\left\{\theta_{ed-1} + \alpha\theta_{ed-2} + \alpha^2\theta_{ed-3}\ldots\right\}. \tag{4}$$

The Eq. (4) can be simplified as follows:

$$\theta_{rm} = (1-\alpha)\,\theta_{ed-1} + \alpha\theta_{rm-1}, \tag{5}$$

θ_{rm} - running mean external temperature for the evaluated day, [°C];
θ_{rm-1} - running mean external temperature for the previous day, [°C];
θ_{ed-1} - daily mean external temperature for the previous day, [°C];
θ_{ed-2} - daily mean external temperature two days before the evaluated day, [°C];
θ_{ed-3} - daily mean external temperature three days before the evaluated day, [°C];
α - coefficient from 0 to 1. Its recommended value is 0.8, [$-$].

The degree of utilization of heat gains or thermal heat losses are directly related to the thermal inertia of the building. Based on the inner heat capacity of the building, a time response to changing environmental conditions can be determined as the time constant, which generally indicates the time at which the transient process of a monitored variable decreases from maximum to zero value, if the process proceeds at constant velocity or linearly.

According to the Czech technical standard CSN EN ISO 13790 [4], the constant velocity is given by the equation (6) for cooling moode:

$$\tau_c = \frac{C_m/3600}{H_{tr,adj} + H_{ve,adj}}, \tag{6}$$

τ_c - time constant of the building or building zone in the cooling moode, [h];
C_m - inner heat capacity of the building, [kJ.K^{-1}];
$H_{tr,adj}$ - representative value of the total specific heat flux by heat transfer converted for a thermal difference between the interior and the external environment, [W.K^{-1}].
$H_{ve,adj}$ - representative value of the total specific heat flux by ventilation converted for a temperature difference between the interior and the external environment, [W.K^{-1}].

For determination of the time constant by Comsol Multiphyics, simulation of the tested room cooling under the required initial and boundary conditions was performed. The time constant was determined from the time course of the air temperature inside the room (see Fig. 7).

3 Description of a tested room

Testing was performed on a real room in the building of the Faculty of Applied Informatics of Tomas Bata University in Zlín. The geometry sketch is shown in Fig. 1.

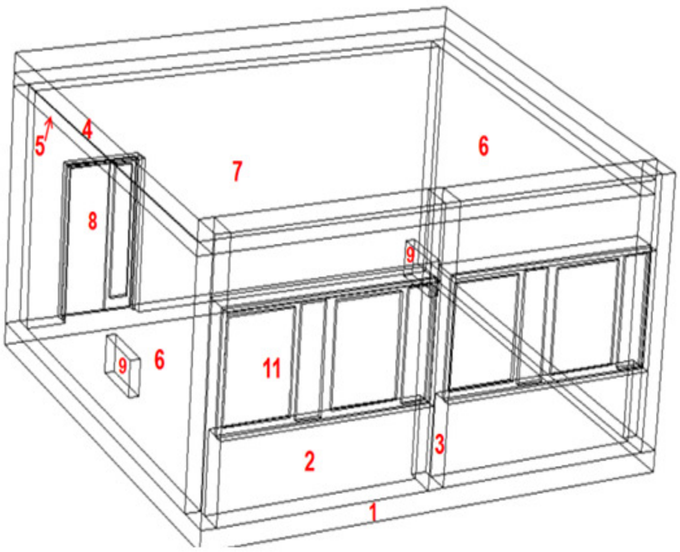

Figure 1: Geometry sketch of the tested room model. 1 - floor, 2 - wall under the windows (outside wall), 3 - reinforced concrete column, 4 - ceiling insulation, 5 - ceiling, 6 - inner sidewall, 7 - the inner rear wall, 8 door, 9 - electrical heaters.

The used geometry is a simplification of reality. Therefore it contains only elements that significantly influence heat flux between the room and its surroundings. Sketch of placement of tested room inside a building is shown in Fig. 2. One of the walls and ceiling of the room are surrounded by the outside environment. Other walls and floor are surrounded by rooms and corridor inside the building. Physical properties of main geometrical elements of the tested room are given in Table 1.

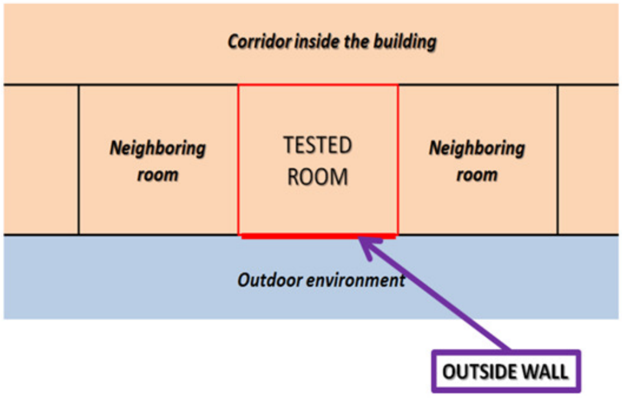

Figure 2: Sketch of placement of tested room inside a building

Table 1: Physical properties of main geometrical elements of the tested room

Geometrical element	*Thermal conductivity* [W.m^{-1}.K^{-1}]	*Density* [kg.m^{-3}]	*Specific thermal capacity* [J.kg^{-1}.K^{-1}]
Inner walls	0.27	900	960
Door frames	58	7850	440
Door	0.11	800	1500
Floor, ceiling structure, reinforced concrete pillar	1.43	2300	1020
Ceiling insulation	0.039	30	1270
Wall under the windows	0.15	800	960
Window frame	0.18	400	2510
Window	0.76	2600	840
Construction above the windows	0.025	2300	1020

4 Results

4.1 Determination of heat loss in the room during cyclic heating and cooling

Testing of the heat loss in the room was carried under cyclic heating and cooling for 9 days. The room was heated by two heaters with the input power of about 2 kW and 3 kW.

For a theoretical calculation we determined the outside air temperature as daily mean air temperature calculated from measured values of the outside air temperature in a given timeframe. Measured outside air temperature we took from meteorological data available on the server of Tomas Bata University in Zlín [9]. The used data are shown in Fig. 3. Table 2 gives the calculated values of the daily mean temperatures. Assumed heat transfer coefficient between the walls of the room and the air inside the building was 8 Wm^{-2}K^{-1}. Assumed heat transfer coefficient between the walls of the room and outside air was 23 Wm^{-2}K^{-1}. The air temperature of neighboring rooms was throughout the experiment between 18 °C and 20 °C.

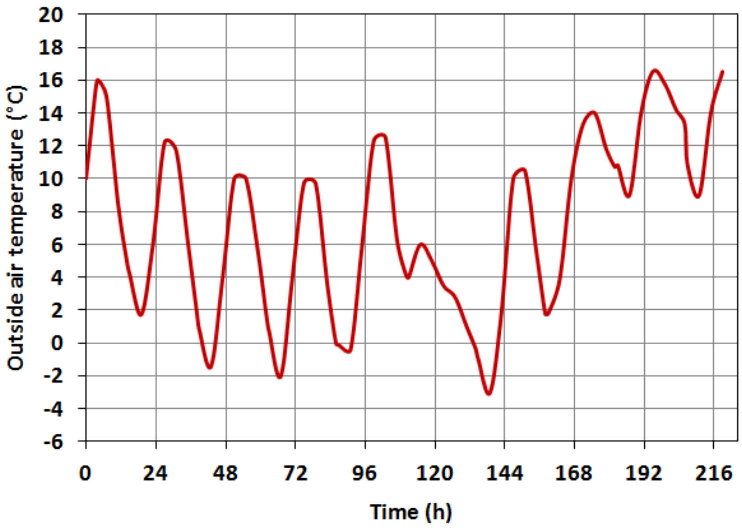

Figure 3: Outside air temperature during cyclic heating of the room - measured data [4].

Table 2: Daily mean external temperature

Day	*Daily mean external temperature* [°C]	*Day*	*Daily mean external temperature* [°C]
1	9.05	6	0.71
2	5.07	7	6.21
3	4.31	8	11.94
4	4.08	9	13.37
5	7.19		

In the Fig. 4 is compared experimentally determined temperature of the air inside the room with the room air temperature determined by simulations in model of the tested room with Comsol Multiphysics. The most significant difference between the measured and simulated values occurred during the first day of the testing, when the maximum deviation between measured and simulated values of temperature was about 1.4 °C and 20 °C. In other days of testing the average deviation was about 0.7 °C and 20 °C. The differences may be due to a simplified model used for computer simulation compared to the real conditions of measurement.

In the Fig. 5 is compared the heat flux through the outside wall obtained by theoretical calculation and computer simulation. The differences between theoretically calculated values and heat flux values obtained by computer simulation are mainly caused by the fact that while the computer simulations were used current measurement values of outside air temperature, the average daily temperature of the outside air was used for theoretical calculating of the heat flux. The results are also influenced by simplifying of the model used for computer simulation in comparison with the real conditions in which the experiment was carried out.

Determination of heat losses through the external wall after 8 days of cyclic heating and cooling of the room we made also by comparing simulation results with theoretical calculations for moving mean outdoor air temperature. The moving mean outdoor air temperature we calculated according to equation (4). Depending on the choice of the coefficient α for calculation of moving mean outdoor air temperature, the heat losses were in the range from 81.95 W to 184.5 W (see Table 3). The heat losses determined by computer simulation were 115 W, which corresponds with theoretically calculated heat losses for coefficient $\alpha = 0.55$.

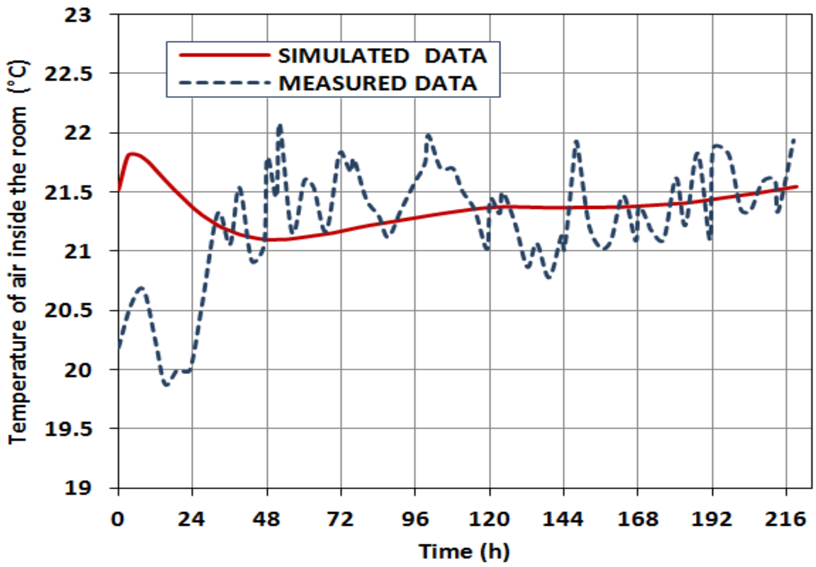

Figure 4: Comparing of the measured air temperature course inside the room with temperature course obtained by computer simulation.

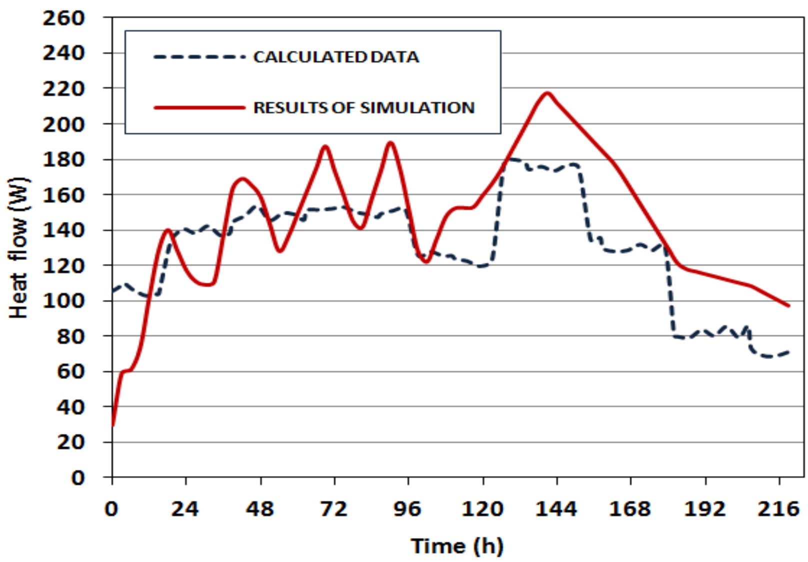

Figure 5: Comparing of theoretically calculated and simulated heat flux through the outside wall of the room.

4.2 Determination of heat loss and time constant by cooling of the room

Testing of the heat losses in the room by cooling was carried for 9 days. Purpose of testing was monitoring of heat losses through outside wall depending on time. Assumed heat transfer coefficient between the walls of the room and the air inside the building was 8 $\mathtt{W.m}^{-2}.\mathtt{K}^{-1}$. Assumed heat transfer coefficient between the walls of the room and outside air was 23 $\mathtt{W.m}^{-2}.\mathtt{K}^{-1}$. The air temperature of neighboring rooms and external air temperature was throughout the experiment 0 °C.

In the Fig. 6 - Fig. 7 are shown results of simulation by Comsol Multiphysics. Simulated course of air temperature in the middle of the room is shown in the Fig. 7. The Fig. 6 shows distribution of air and walls temperature in the tested room is selected times of cooling. In the Fig. 8 is seen decrease of the external wall temperature during cooling. Decrease of the heat flux in the external wall during cooling is seen in the Fig. 9.

Table 3: Theoretically calculated running mean external temperature and heat loss through the external wall after 8 days of cyclic heating and cooling of the room

Coefficient α (1)	*Running mean external temperature external temperature* [°C]	*Heat loss through the external wall* (W)
0	11.94	81.95
0.1	11.32	86.62
0.2	10.62	92.65
0.3	9.88	99.08
0.4	9.11	105.72
0.5	**8.33**	**112.45**
0.6	**7.53**	**119.37**
0.7	6.65	127.04
0.8	5.47	137.19
0.9	3.56	153.72
0.9	0.00	184.50

The time constant was determined from the time course of the air temperature inside the room (see Fig. 7). Under the give conditions its value was about 68 hours.

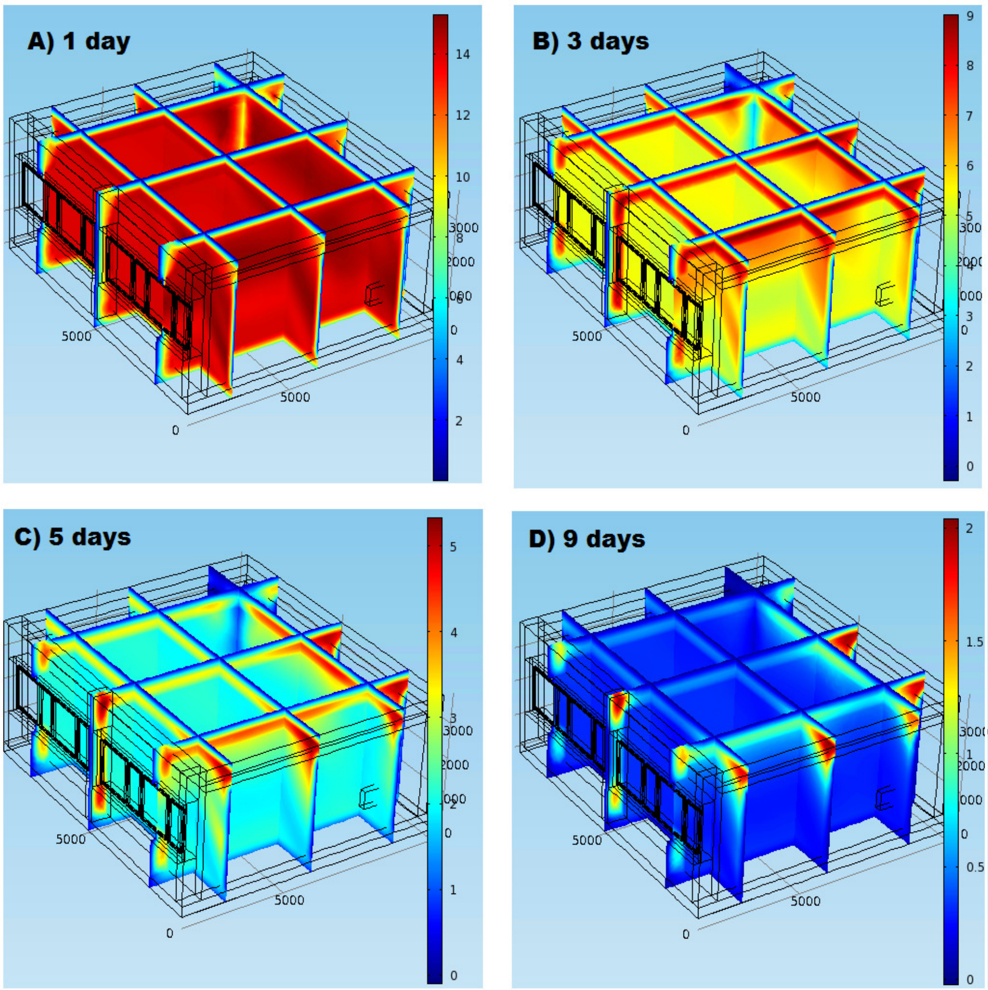

Figure 6: Temperature distribution of air and walls in the tested room after A) 1 day, B) 3 days, C) 5 days, D) 9 days of cooling.

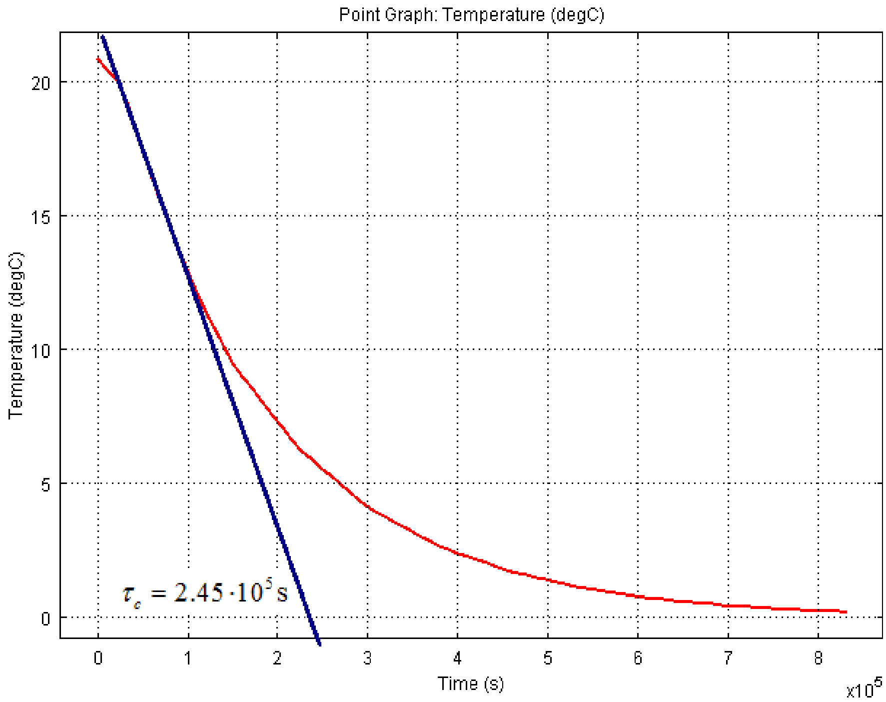

Figure 7: Determination of time constant from air temperature course in the room.

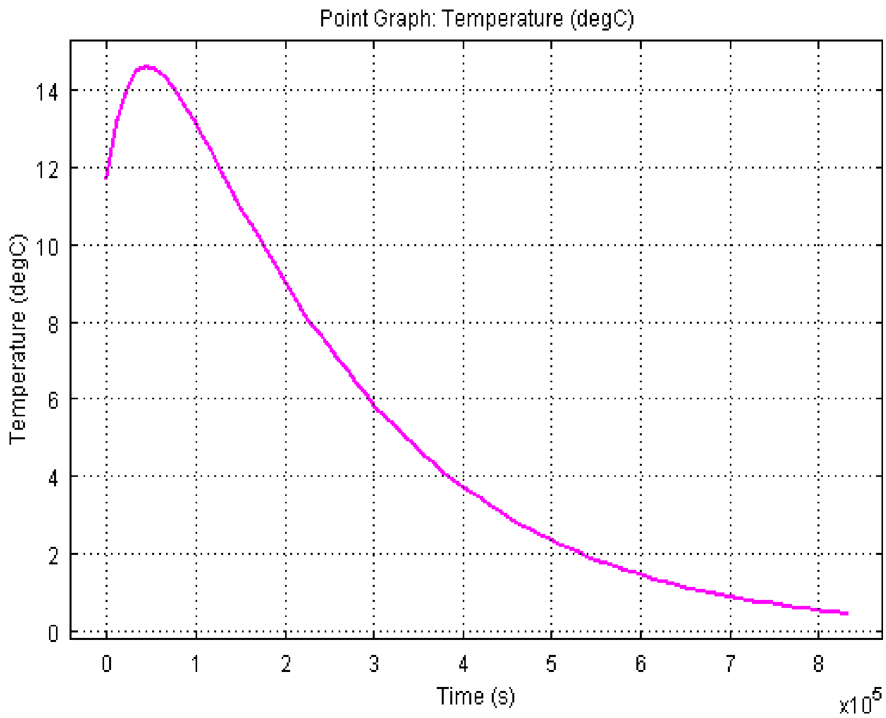

Figure 8: Temperature inside the external wall during cooling of the tested room.

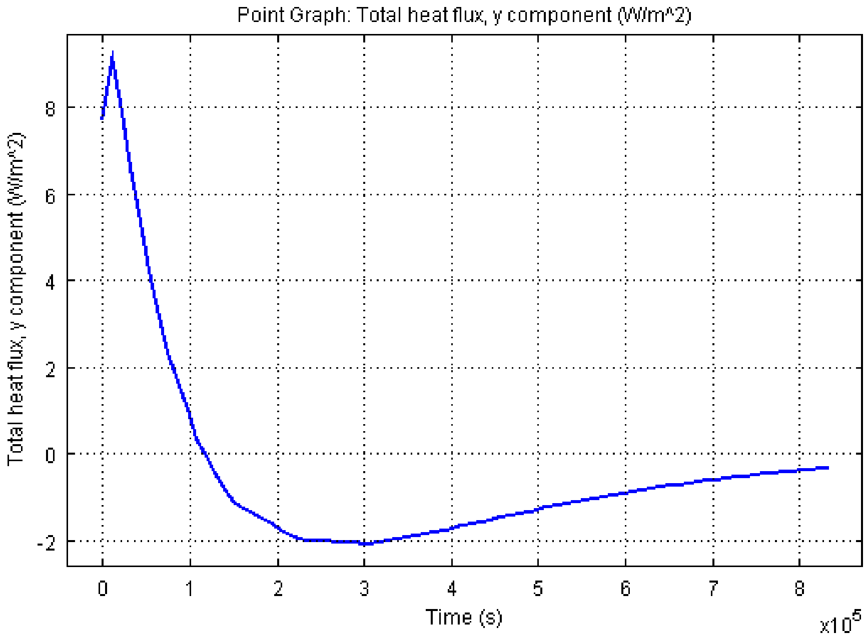

Figure 9: Heat flux through the external wall during cooling of the tested room.

5 Conclusion

For assessment of heat losses in the tested room during its cyclic heating and cooling were compared two methods. The first method was a theoretical calculation of heat flux through the outside wall in accordance with the recommendations described in the Czech Technical Standards CSN EN 15251 and CSN 06220. The second method was computer simulation of non-stationary heat transfer in the simplified model of the tested room for the required initial and boundary conditions. Comparison of the results showed that the theoretical calculation of heat loss through the outside wall influenced by errors caused by using the average daily temperature and by selecting values between 0 - 1 as coefficient α for calculation of a running mean external temperature.

For testing room was established value of the coefficient $\alpha = 0.55$, for which the heat losses determined by computer simulation were in accordance with the theoretically calculated heat losses. By computer simulation of the room cooling were acquired courses of the temperature and heat flux in the walls of the room. From the course of air temperature in the cooling room was determined time constant $\tau_c = 68$ hours under given conditions.

Further research will be focused on testing of influence of extenal wall thermal insulating on thermal stability of the room.

Acknowledgment

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