Computer Evaluation of Results by Room Thermal Stability Testing

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Abstract: The paper deals with the use of computer tools for assessing of the thermal stability of buildings. It describes the procedure developed for determining of a time constant for cooling down of the room and a coefficient α whose values are related to the building's thermal-accumulation properties. The developed methodological procedure is based on processing of the data obtained by measuring in the real building object, computer simulations in COMSOL Multiphysics software and subsequent processing of the output data in MAPLE and MATLAB software with regard to compliance with valid European and Czech technical standards used in building industry and Architecture. The studied model of the room showed the dependence of the time constant and the coefficient α on thickness and specific heat capacity of the thermal insulation of the external wall under the selected winter conditions. The studied example also proved correlation between the coefficient α and the time constant of the room.

Key–Words: Thermal stability assessment, cooling down of the room, coefficient α, time constant of the room, computer simulation

1 Introduction

In terms of optimization, the design of modern buildings is emphasis on minimizing energy consumption while minimizing investment and operating costs and keeping the required internal environment parameters. These costs strongly depend on the building's thermal storage parameters and can therefore be influenced by their construction.

However, due to the complexity of physical processes, a theoretical testing of the thermal stability in the design of new building structures or in their reconstruction is very difficult. In terms of the assessment of the heat accumulation parameters, consideration should be given to the time delay of the response of the indoor environment to changing outdoor conditions. These problems are solved in the technical standard CSN EN 13790 [1] and related CSN EN 13792 [2], CSN EN 13786 [3], CSN EN 15251 [4] and CSN 06 0220 [5] and, to a certain extent, CSN 73 0540 [6].

But to find a complex solution to this problem according to CSN EN 13790 [1] and related standards is difficult and the most accurate methods are sought using modern computer tools using simulation methods based on numerical solution of non-stationary multiphysical processes on models describing studied objects under simplified conditions.

From this perspective, we deal with testing of the factors that influence thermal stability of building by combination of computer simulation in the COMSOL Multiphysics user interface and theoretical calculations with respect to above-mentioned technical standards used in the building industry. Possibilities of use COMSOL Multiphysics for testing of thermal stability of buildings were verified in the papers [7], [8].

In this paper we follow the paper [8], in which the heat losses through the uninsulated outside wall were compared by the theoretical calculation. Now, we describe the procedure by which it is possible to combine both computer simulation and theoretical calculations programmed in MAPLE and MATLAB user interfaces to determine the heat losses of the room under simplified assumptions for the assessment of thermal insulating materials of the external wall or the heat-accumulation properties of the room to be tested.

In the studied example we show dependence of the time constant in case of cooling down of the room and the coefficient α on thickness and specific heat capacity of the thermal insulation of the external wall.

2 Physical description of the studied problem

For computer simulation by COMSOL Multiphysics software we use Laminar Flow Interface of the Conjugate Heat Transfer Module, which is used primarily to model slow-moving flow in environments where temperature and energy transport are also an important part of the system and application, and must coupled or connected to the fluid-flow in some way. The interface solves the Navier-Stokes equations together with an energy balance assuming heat flux through convection and conduction. The density term is assumed to be affected by temperature and flow is always assumed to be compressible [9].

Finite Element Equations for Heat Transfer A basic equation of non-stationary heat transfer in an isotropic body can be described by equation (1) [10]:

$$-\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)+\Phi=\varrho c_p\frac{\partial T}{\partial t} \qquad (1)$$

where:
$q_x,\ q_y,\ q_z$ - components of heat flow density, $\left[\mathrm{W\cdot m^{-2}}\right]$;
$\Phi=\Phi(x,y,z,t)$ - inner heat-generation rate per unit volume, $\left[\mathrm{W\cdot m^{-3}}\right]$;
ϱ - material density, $\left[\mathrm{kg\cdot m^{-3}}\right]$;
c_p - heat capacity, $\left[\mathrm{J\cdot K^{-1}}\right]$;
T - temperature, $[\mathrm{K}]$;
t - time, $[\mathrm{s}]$.

According to Fouriers law the components of heat flow can be expressed as follows [10]:

$$q_x=-\lambda\frac{\partial T}{\partial x},\ q_y=-\lambda\frac{\partial T}{\partial y},\ q_z=-\lambda\frac{\partial T}{\partial z} \qquad (2)$$

where:
λ - thermal conductivity of the media, $\left[\mathrm{W\cdot m^{-1}K^{-1}}\right]$.

Substitution of Fouriers relations (2) into equation (1) gives the basic heat transfer equation [10]:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\Phi=\varrho c_p\frac{\partial T}{\partial t} \qquad (3)$$

It is assumed that the boundary conditions can be of the following types [10]:

1. Specified temperature: $T_s = T_1(x,y,z,t)$ on S_1.
2. Heat flow density: $q_s=q(x,y,z,t)$ on S_2.
3. Convection boundary conditions: $q_xn_x+q_yn_y+q_zn_z=h\left(T_s-T_e\right)+q_r$ on S_3.

where:
h - heat transfer coefficient, $\left[\mathrm{W\cdot m^{-2}K^{-1}}\right]$;
T_s - unknown surface temperature, $[\mathrm{K}]$;
T_e - convective exchange temperature, $[\mathrm{K}]$;
q_s - heat flow density on the surface, $\left[\mathrm{W\cdot m^{-2}}\right]$;
q_r - incident radiant heat flow per unit surface area, $\left[\mathrm{W\cdot m^{-2}}\right]$;
$q_x,\ q_y,\ q_z$ - components of heat flow density, $\left[\mathrm{W\cdot m^{-2}}\right]$.

For initial temperature field for a body at the time $\tau=0$ it holds [10]:

$$T(x,y,z,t)=T_0(x,y,z) \qquad (4)$$

By determination of the heat losses from the room we assumed that the heat transfer between the room air and the surroundings is the heat transfer through its walls.
In this case, the heat flow can be described by equation (7) [5]:

$$\Phi=A\cdot U\left(\theta_{in}(t)-\theta_{out}(t)\right), \qquad (5)$$

where:
A - heat transfer surface, $\left[\mathrm{m^2}\right]$;
U - overall heat transfer coefficient, $\left[\mathrm{W\cdot m^{-2}K^{-1}}\right]$;
θ_{in} - temperature of air inside the room, $[{}^\circ\mathrm{C}]$;
θ_{out} - temperature of air outside the room, $[{}^\circ\mathrm{C}]$;
Φ - heat flux through the external wall, $[\mathrm{W}]$;
t - time, $[\mathrm{s}]$.

The overall heat transfer coefficient (U) through the multilayer wall of the room can be computed according to equation (6) [5]:

$$U=\frac{1}{\frac{1}{h_{in}}+\frac{1}{h_{out}}+\sum_{j=1}^{n}\frac{\delta_j}{\lambda_j}} \qquad (6)$$

where:
h_{in} - heat transfer coefficient of the inner wall surface, $\left[\mathrm{W\cdot m^{-2}K^{-1}}\right]$;
h_{out} - heat transfer coefficient of the outside wall surface, $\left[\mathrm{W\cdot m^{-2}K^{-1}}\right]$;
δ_j - thickness of the layer, $[\mathrm{m}]$;
λ_j - thermal conductivity of the layer, $\left[\mathrm{W\cdot m^{-1}K^{-1}}\right]$;
n - number of the layers, $[-]$.

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 a 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 [1], the time constant τ_c for cooling mode is given by the equation (7):

$$\tau_c = \frac{C_m/3.6}{H_{tr,adj} + H_{ve,adj}}, \tag{7}$$

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

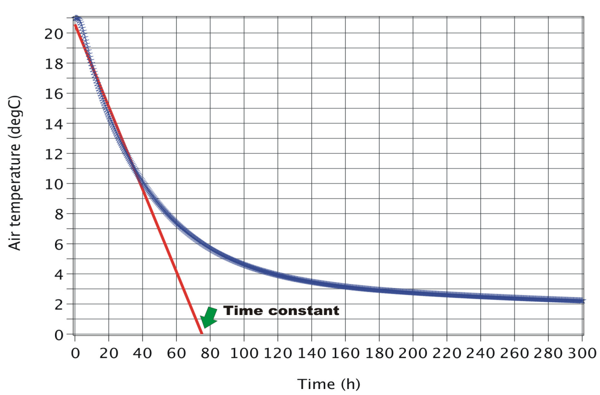

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Figure 1: Determination of time constant from air temperature course in the room.

It is obvious that the time course of heating or cooling of the room strongly depends on the outside air temperature. In this regard, it is necessary to consider the thermal accumulation properties of the room, as a result of which the response of the indoor environment is caused by some time delay in the changing environment conditions. Therefore, an effort is made to simplify the solution, for example by expressing the storage properties of a building by room time constant according to CSN 06 0220 [5] or by so-called sliding temperature running mean external temperature according to CSN EN 15251 (8) [4]:

$$\theta_{rm} = (1-\alpha)\left\{\theta_{ed-1} + \alpha \cdot \theta_{ed-2} + \alpha^2 \cdot \theta_{ed-3} \ldots\right\}, \tag{8}$$

or by equation (9):

$$\theta_{rm} = (1-\alpha)\,\theta_{ed-1} + \alpha \cdot \theta_{rm-1}. \tag{9}$$

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

The aim of our research is to find a relationship between the time constant and the constant α.

3 Method used for the studied problem solving

Our currently tested principle for assessing of the room thermal stability using the theoretical calculations and computer simulations supported by experimental measurements in laboratory or real conditions is based on these steps:

- Build a simplified model of the tested room in user interface of COMSOL Multiphysics.
- Computer simulation of temperature distribution in the tested model of the room for 9 days with the initial and boundary conditions obtained by measuring on a real object of the room (the course of the outdoor air temperature, or the ambient air temperatures, if any, of the adjoining rooms).
- Export data describing the air temperature at the centre of the room calculated in COMSOL Multiphysics to the user interface of software MAPLE, where the time constant is determined by Least square method from the linear part of the curve of temperature decrease as is shown in Fig. 1).
- Numerical determination of the optimal value of the coefficient α for calculating the running mean external temperature according to equation (8) or (9) and then the heat losses through the outside wall of the

room after 8 days of testing so that the heat losses calculated according to [5] equal to the heat losses determined by the computer simulation.

3.1 Numerical calculation of the parameters in MAPLE user interface

The numerical calculation of the optimal value of the coefficient α for the running mean external temperature we programmed in user interface of MAPLE software. The source code of the programmed procedure consists of these main parts:
Calculation of the overall heat transfer coefficient according to equation (6):

```
> U:=1/((1/h_in)+(1/h_out)+
> (delta_1/lambda_1)+
> (delta_2/lambda_2));
```

$$U := \frac{1}{\frac{1}{h_in} + \frac{1}{h_out} + \frac{delta_1}{lambda_1} + \frac{delta_2}{lambda_2}}.$$

Calculation of the daily mean temperature θ_{di} of the external air for tested 8 days according to equation (10):

$$\theta_{di} = \frac{di_{\ 7h} + di_{\ 14h} + 2di_{\ 21h}}{4}, \qquad (10)$$

where $di_{\ 7h}, di_{\ 14h}, di_{\ 21h}$ are external air temperatures measured for the given day at 7:00 AM, 2:00 PM and 9:00 PM. In Maple we programmed the calculation by commmands:

```
> theta_d1:=
> (d1_7h+d1_14h+2*d1_21h)/4;
```

$$theta\_d1 := 1/4d1\_7h + 1/4d1\_14h + 1/2d1\_21h$$

```
> theta_d2:=
> (d2_7h+d2_14h+2*d2_21h)/4;
```

$$theta\_d2 := 1/4d2\_7h + 1/4d2\_14h + 1/2d2\_21h$$

$$\vdots$$

Calculation of the running mean external temperature for given heat flow through the external wall after 8 days of cooling down of the room:

```
> theta_rm:=(U*theta_in-Theta)/U;
```

$$theta\_rm := \frac{(U * theta_in - Theta)}{U}$$

Numerical solution of the coefficient α from the equation (11):

$$theta\_rm = (1-\alpha)(X1 + X2 + X3) \qquad (11)$$

where

$$X1 = theta_d8 + alpha * theta_d7 + \alpha^2 theta\_d6 + \alpha^3 theta\_d5 + \alpha^4 theta\_d4 + \alpha^5 theta\_d3 + \alpha^6,$$

$$X2 = \alpha^6 (1/4d2\_7h + 1/4d2\_14h + 1/2d2\_21h),$$
$$X3 = \alpha^7 (1/4d1\_7h + 1/4d1\_14h + 1/2d1\_21h).$$

Notation for the numerical solution of coefficient α in MAPLE user interface is:

```
> alpha:=fsolve(theta_rm=
> (1-alpha)*(X1+X2+X3),alpha);
```

List of symbols used in the above described souce code:
U - overall heat transfer coefficient, , $[\mathrm{W.m^{-2}.K^{-1}}]$;
h_in - heat transfer coefficient of the inner wall surface, $[\mathrm{W \cdot m^{-2}K^{-1}}]$;
h_out - heat transfer coefficient of the outside wall surface, $[\mathrm{W \cdot m^{-2}K^{-1}}]$;
$delta\_1$ - thickness of the external wall, $[\mathrm{m}]$;
$delta\_2$ - thickness of the thermal insulation, $[\mathrm{m}]$;
$lambda\_1$ - thermal conductivity of the external wall, $[\mathrm{W \cdot m^{-1}K^{-1}}]$;
$lambda\_2$ - thermal conductivity of the thermal insulation, $[\mathrm{W \cdot m^{-1}K^{-1}}]$;
$theta\_di$ - external air temperatures measured for the given day $i = 1, 2..., 8$ of the testing, $[°\mathrm{C}]$;
di_7h, di_14h, di_21h - external air temperatures measured for the given day $i = 1, 2..., 8$ of the testing at 7:00 AM, 2:00 PM and 9:00 PM, $[°\mathrm{C}]$;
$theta_rm$ - running mean external temperature, $[°\mathrm{C}]$;
$Theta$ - heat flow density through the outside wall of the room after 8 days of testing, $[\mathrm{W \cdot m^{-2}}]$;
$alpha$ - coefficient alpha, $[1]$.

3.2 Example of the suggested method using

We demonstrate the above described method for assesment of thermal stability of the room which simplified geometric model is shown in Fig. 2. It contains only elements that significantly affect the heat flow between the room and the surroundings. Aim of the testing was to evaluate the influence of the thickness and heat capacity of a thermal insulation of the external wall on the time course of the cooling down of the room.

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

Geometrical element	**Thermal conductivity** $\left[\mathrm{W.m^{-1}.K^{-1}}\right]$	**Density** $\left[\mathrm{kg.m^{-3}}\right]$	**Specific heat capacity** $\left[\mathrm{J.kg^{-1}.K^{-1}}\right]$
Inner and external walls	0.1765	817	953
Floor	1.43	2300	1020
Ceiling	0.8185	1251	1021
Window frame	0.20	420	2510
F Ceiling insulation	0.039	30	1270
Thermal insulation of external wall	0.4	400	1000, 3000, 5000, 7000

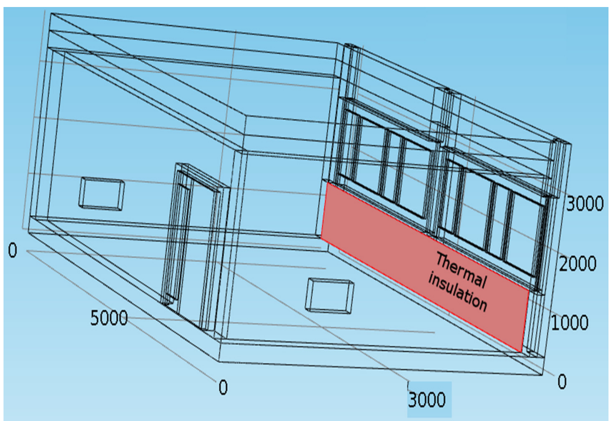


Figure 2: Geometry sketch of the tested room model.

The conditions used for computer simulations and theoretical calculations are:

- initial air temperature inside the room 21 °C,
- air temperature of all neighboring rooms 0 °C,
- heat transfer coefficient between the walls of the room and the air inside the building 8 $\mathrm{W.m^{-2}.K^{-1}}$,
- heat transfer coefficient between the walls of the room and outside air 23 $\mathrm{W.m^{-2}.K^{-1}}$,
- thickness of the inner walls, ceiling and floor 30 cm,
- physical properties of all elements of the models shows Table 1,
- course of outside air temperature is shown in Fig. 3.

The results of our experiment are presented in Figs 4 - 7. Fig. 4 shows a decrease of the air temperature inside the room during its cooling down in dependence on the thermal insulation thickness.

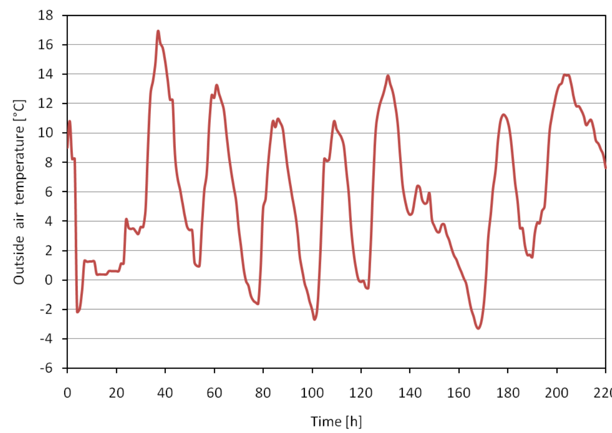
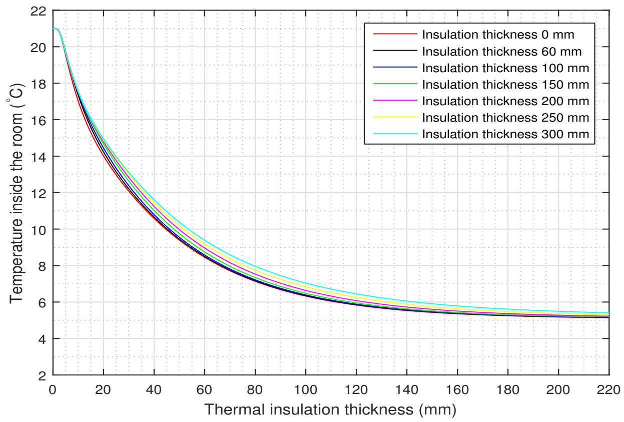


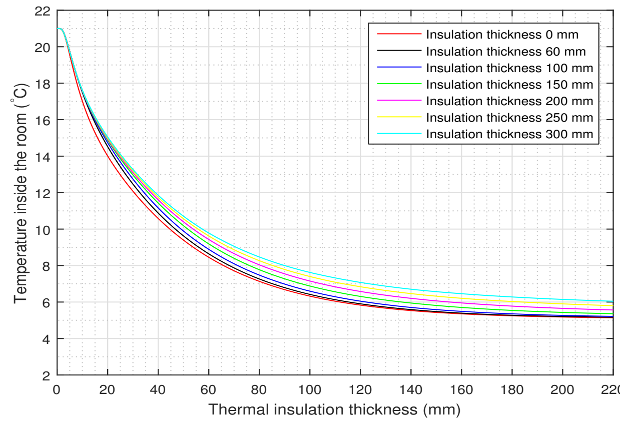
Figure 3: Course of outside air temperature used for computer simulation - measured data.

In Fig. 4a are shown temperature courses for thermal insulation with specific heat capacity of 1000 $\mathrm{J.kg^{-1}.K^{-1}}$, in Fig. 4b for thermal insulation with specific heat capacity of 3000 $\mathrm{J.kg^{-1}.K^{-1}}$, in Fig. 4c with 5000 $\mathrm{J.kg^{-1}.K^{-1}}$, and Fig. 4d with 7000 $\mathrm{J.kg^{-1}.K^{-1}}$. In all tested cases the simulations were compared for wall of 200 mm thickness and thermal insulation thickness between 20 and 300 mm. It is evident, that maximum temperature decrease occurred for the wall without thermal insulation and that the temperature decrease has decreased with the increasing thickness and specific heat capacity of the thermal insulation.

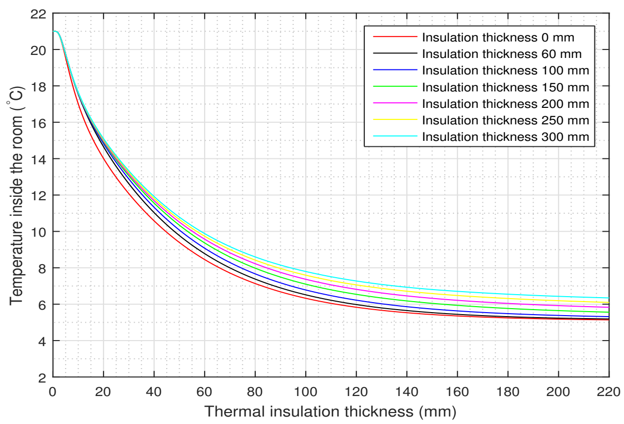
Dependence of the time constant on thermal insulation thickness and specific heat capacity determined by the linear regression for the data obtained by computer simulation is shown in Fig. 5.



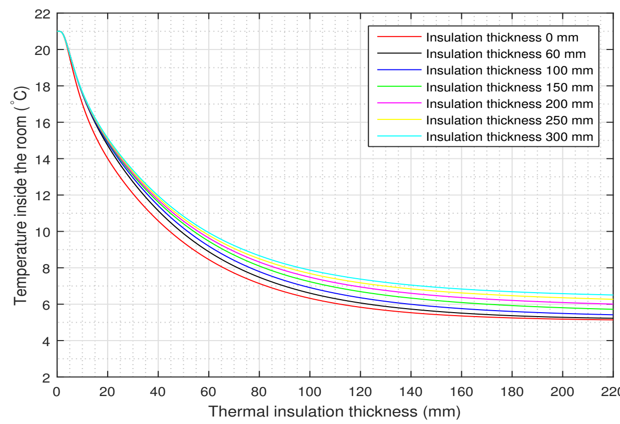
(a) $c_p = 1000\,\mathrm{J.kg^{-1}.K^{-1}}$



(b) $c_p = 3000\,\mathrm{J.kg^{-1}.K^{-1}}$

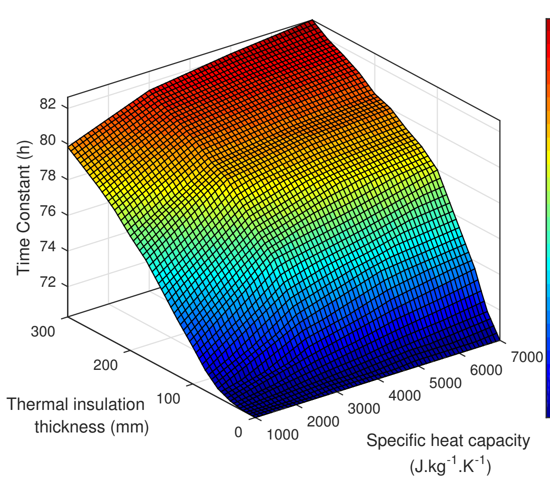


(c) $c_p = 5000\,\mathrm{J.kg^{-1}.K^{-1}}$

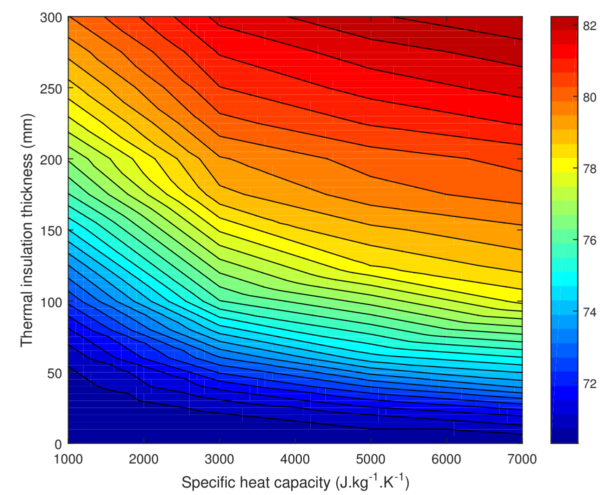


(d) $c_p = 7000\,\mathrm{J.kg^{-1}.K^{-1}}$

Figure 4: Dependence of the air temperature decrease on thickness of the external wall insulation with specific heat capacity (a) $1000\,\mathrm{J.kg^{-1}.K^{-1}}$, (b) $3000\,\mathrm{J.kg^{-1}.K^{-1}}$, (c) $5000\,\mathrm{J.kg^{-1}.K^{-1}}$, (d) $7000\,\mathrm{J.kg^{-1}.K^{-1}}$.

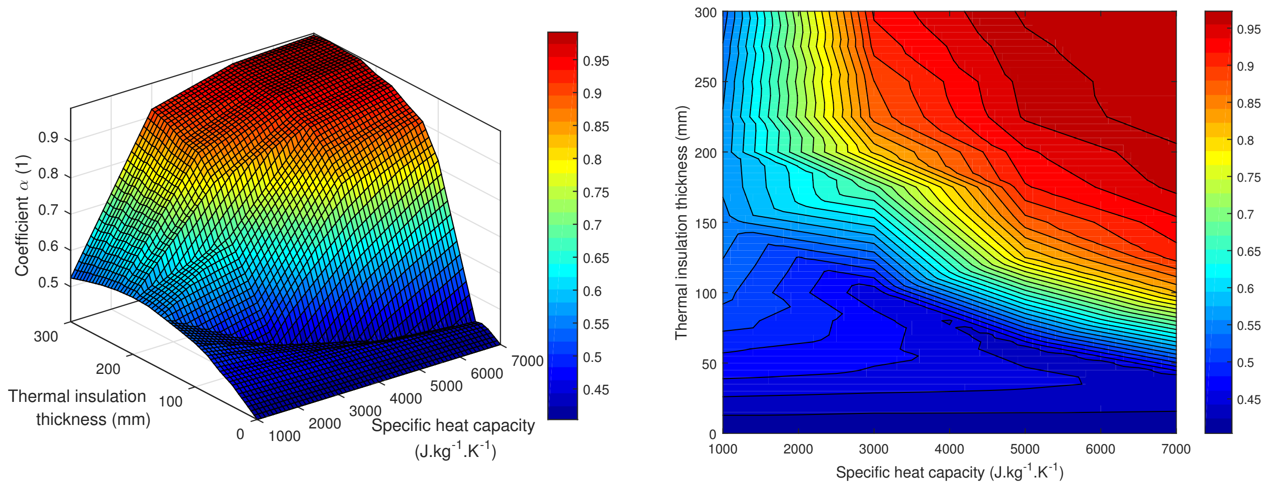


(a) Time constant - distribution in 3D



(b) Time constant - distribution in 2D

Figure 5: Dependence of the time constant on specific thermal capacity and thickness of the external wall thermal insulation (a) as a 3D plot, (b) as a 2D distribution.



(a) Coefficient α - distribution in 3D

(b) Coefficient α - distribution in 2D

Figure 6: Dependence of the coefficient α on specific thermal capacity and thickness of the external wall thermal insulation (a) as a 3D plot, (b) as a 2D distribution.

Fig. 5a shows increase of the time constant with increasing thermal insulation thickness and specific heat capacity as a 3D plot. Fig. 5b shows distribution of the time constant values as a 2D distribution. The minimum increase of the time constant was observed for thermal insulation with specific heat capacity of 1000 $J.kg^{-1}.K^{-1}$. Under the tested conditions, the time constant increased approximately by 9.5 hours for the wall with thermal insulation thickness of 300 mm and compared to the time constant for the external wall without the thermal insulation. The maximum increase of the time constant was observed for thermal insulation with specific heat capacity of 7000 $J.kg^{-1}.K^{-1}$. In this case the time constant increased approximately by 12.3 hours for the wall with thermal insulation thickness of 300 mm compared to the time constant for the room external wall without the thermal insulation.

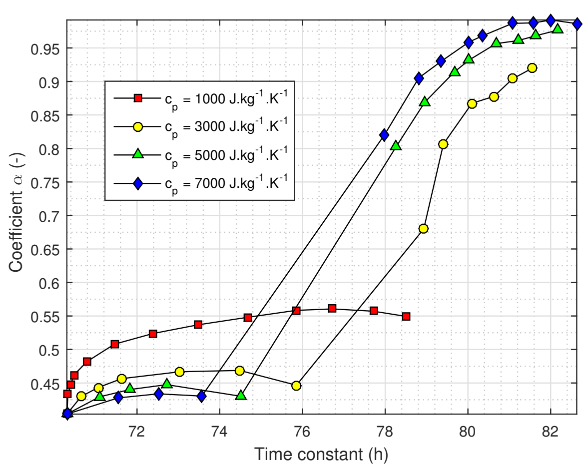


Figure 7: Dependence of the air temperature decrease on thickness of the external wall insulation.

In Fig. 6 is presented dependence of the coefficient α on the thermal insulation thickness and specific heat capacity, which is required to calculate the daily mean temperature of the external air (8) or (9) in accordance with CSN EN 15251 [4]. Fig. 6a shows increase of the coefficient α with increasing thermal insulation thickness and specific heat capacity as a 3D plot. Fig. 6b shows distribution of coefficient α values as a 2D distribution. The experimental results show that under the conditions considered, the coefficient α strongly depends on the thickness of the external wall thermal insulation. It is evident that if the wall be insulated by material with higher specific heat capacity and thickness, the air temperature and the time of cooling down the room increase. As it was mentioned, the value recommended for technical calculations is the coefficient α is 0.8 [4]. But under the studied conditions value between 0.40 (for the wall without thermal insulation) and 0.99 (for the wall with thermal insulation thickness of 300 mm and specific heat capacity of 7000 $J.kg^{-1}.K^{-1}$) was observed. The minimum increase of the coefficient α was observed for thermal insulation with specific heat capacity of 1000 $J.kg^{-1}.K^{-1}$. The value of the coefficient α increased approximately by 0.12 for the wall with thermal insulation thickness of 300 mm and compared to the coefficient α for the room external wall without the thermal insulation. The maximum increase of the coefficient α was observed for thermal insulation with specific heat capacity of 7000 $J.kg^{-1}.K^{-1}$ when its value increased approximately by 0.58 for the wall with thermal insulation thickness of 300 mm compared to the coefficient α for the room external wall without the thermal insulation.

Fig. 7 summarizes the relationship between the calculated values of the coefficient α and time constant for the tested thermal insulation with the specific heat capacity 1000, 3000, 5000, 7000 $\mathrm{J.kg^{-1}.K^{-1}}$. It is evident that for increasing specific heat capacity the thermal stability of the room increases due to better thermal accumulation properties of the wall. Under the studied conditions the thermal accumulation was not too high for the wall covered by thermal insulation with a specific heat capacity of 1000 $\mathrm{J.kg^{-1}.K^{-1}}$. But insulated materials with a specific heat capacity of 3000, 5000, 7000 $\mathrm{J.kg^{-1}.K^{-1}}$ had a steep increase of the time constant and the coefficient α values at the insulation thickness of about 100 mm, 70 mm and 50 mm.

4 Conclusion

In the paper using of the developing methodology for assesing of thermal stability the of buildings was presented. The suggested procedure is based on combination of both computer simulation and theoretical calculations to determine the heat losses of the room under simplified assumptions with respect to Czech and European technical standards used in construction and architecture.

The proposed procedure was tested by the assessment of the heat-accumulation properties and thermal insulating materials of the external wall. The studied model of the room showed dependence of the time constant and the coefficient α on the thermal insulation thickness and specific heat capacity under the selected winter conditions.

The studied example also examined the correlation between the coefficient α and the time constant of the room. However, a further set of experiments under another conditions will need to be performed for a thorough assessment of the dependence of the monitored parameters, as well as a more detailed analysis of the resulting values will be performed.

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