Modelling of Passive Cooling of a Wooden House by COMSOL Multiphysics

(Modelování pasivního chlazení dřevostavby v prostředí COMSOL Multiphysics)

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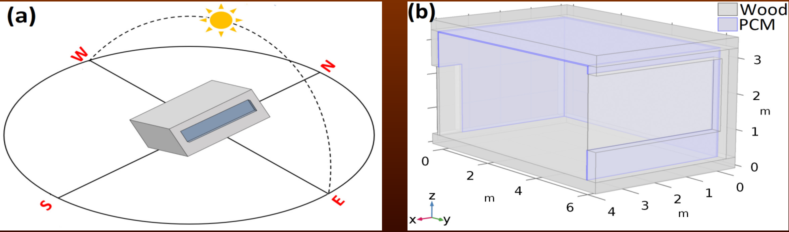
Goal of the study

- The goal of simulations was to assess the effect of covering walls inside the house with a PCM on its passive cooling under warm summer days. A model of a house without the PCM coverage was compared with models of houses in which the PCM was located on all walls except a floor and on a wall opposite the window.
- Computer simulations were performed by the COMSOL Multiphysics software.
- A model of a house without the PCM coverage was compared with models of houses in which the PCM was located on all walls except a floor and on a wall opposite the window.

Methodology

Model Description

- The model includes tools for modelling of the non-stationary heat transfer by conduction, convection, and radiation.
- Three variants of the model are compared with regard to the coverage of the walls with the PCM. Model *M*1 is represented by a house whose construction consists only of wooden walls without PCM coverage. In model *M*2, the wooden walls, and ceiling of the house are covered by a thin layer of the PCM. In model *M*3, only a wall opposite the window (a back wall) is covered by the PCM.



Physical Background

A governing equation (1) describing the non-stationary heat transfer in a house covered by PCMs [2, 3]:

$$\nabla\left(-\lambda\nabla T\right)+\varrho c_p v\nabla T+\varrho c_p\frac{\partial T}{\partial t}=\Phi \tag{1}$$

The specific heat capacity c_p of the PCM includes the latent heat and can be described by equation (2) [3]:

$$c_p=\frac{1}{\varrho}\left(\vartheta\varrho_{phase1}c_{p\ phase1}+\left(1-\vartheta\right)\varrho_{phase2}c_{p\ phase2}\right)+L\frac{\partial\alpha_m}{\partial T} \tag{2}$$

where *phase*1 represents a material in a phase 1 and *phase*2 represents material in a phase 2. ϑ denotes their volume fraction and L is the latent heat.

A mass fraction of the solid and liquid phases α_m can be expressed as follows:

$$\alpha_m=\frac{1}{2}\frac{\left(1-\vartheta\right)\varrho_{phase2}-\vartheta\varrho_{phase1}}{\vartheta\varrho_{phase1}+\left(1-\vartheta\right)\varrho_{phase2}} \tag{3}$$

Physical Background

For an assumption of a smooth transition over ∇T, with a phase mass fraction ϑ, it holds:

$$\varrho = \vartheta \varrho_{phase1} + (1 - \vartheta)\, \varrho_{phase2}. \tag{4}$$

The effective thermal conductivity λ is defined as:

$$\lambda = \vartheta \lambda_{phase1} + (1 - \vartheta)\, \lambda_{phase2}. \tag{5}$$

The temperature θ_s and heat flow density q on a surface were assumed and a convective boundary condition can be described by equation (6):

$$q_x n_x + q_y n_y + q_z n_z = h\,(\theta_s - \theta_e) + q_r. \tag{6}$$

where: the heat transfer coefficient h, surface temperature θ_s, convective exchange temperature θ_e. q_r is the incident radiant heat flow per unit surface area. A condition describing the heat transfer by radiation:

$$q_r = \varepsilon\sigma \left(T_s^4 - T_{amb}^4 \right) \tag{7}$$

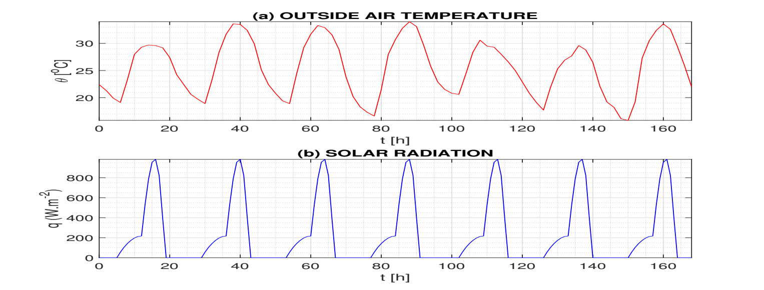
ε is the surface emissivity, T_s is the surface thermodynamical temperature, T_{amb} is the thermodyn. ambient temperature. σ is Stephan-Boltzmann constant.

Simulation Conditions

Table: Properties of materials used in the tested models.

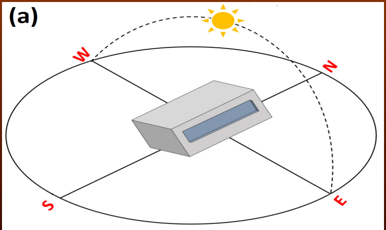
Material	Thermal conductivity $[W/(m \cdot K)]$	Density $[kg/m^3]$	Specific heat capacity $[J/(kg \cdot K)]$	Emissivity [1]
Wood	0.18	400	2510	0.89
Glass	0.76	2600	840	0.96
PCM	0.18[1)] 0.14[2)]	800	9000	0.99

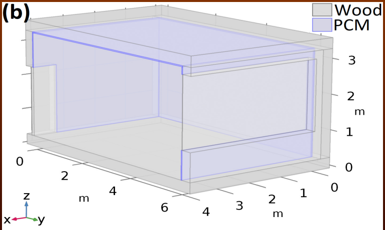
1) In solid phase, 2) In liquid phase



Simulation Conditions

- The supposed location: longitude 17.6630°E, latitude 49.2240°N, and altitude 250 meters above sea level.
- The internal length was 8 m. The width was 6 m and the height was 3 m. The PCM layer thickness was 30 mm.
- The phase change temperature of the PCM was 22 $^{\circ}\mathrm{C}$. The latent heat from solid and liquid phase 200 $\mathrm{kJ/kg}$, and the transition interval was 4 $^{\circ}\mathrm{C}$.

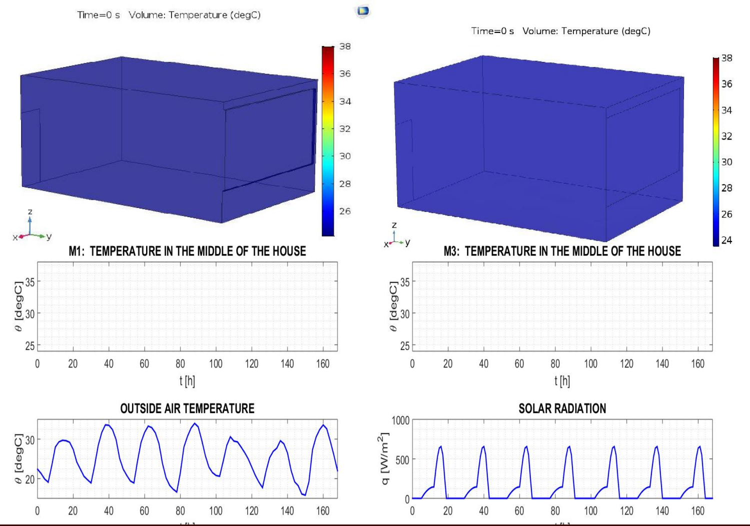




Results of the Simulations

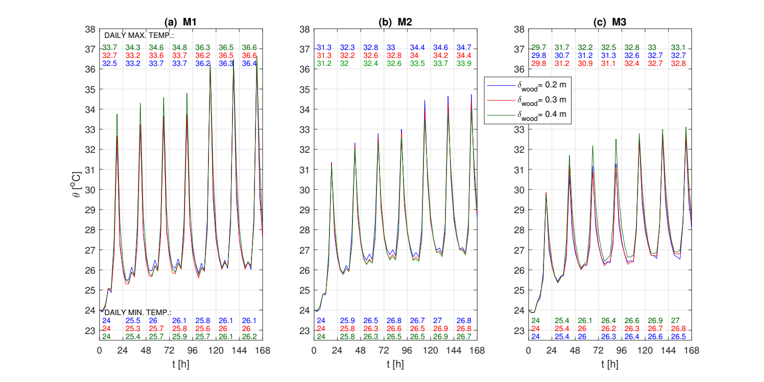
Time evolution of the air temperature

Left: *M*1 (House without PCM), Right: *M*3 (PCM covers a back wall)



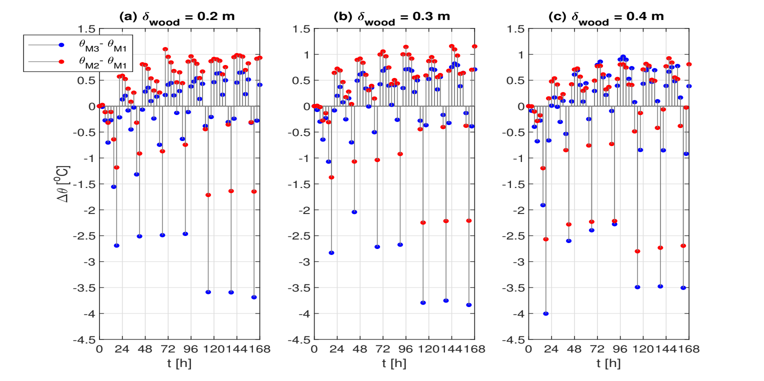
The time evolution of the air temperature in the center of the house

- The time evolution of the air temperature in the center of the house; (a) model *M*1: house without the PCM coverage; (b) model *M*2: house with all walls (except the floor) covered by the PCM; (c) model *M*3: house in which only the back wall is covered by the PCM. The wooden wall thickness is 0.2 m, 0.3 m, and 0.4 m.



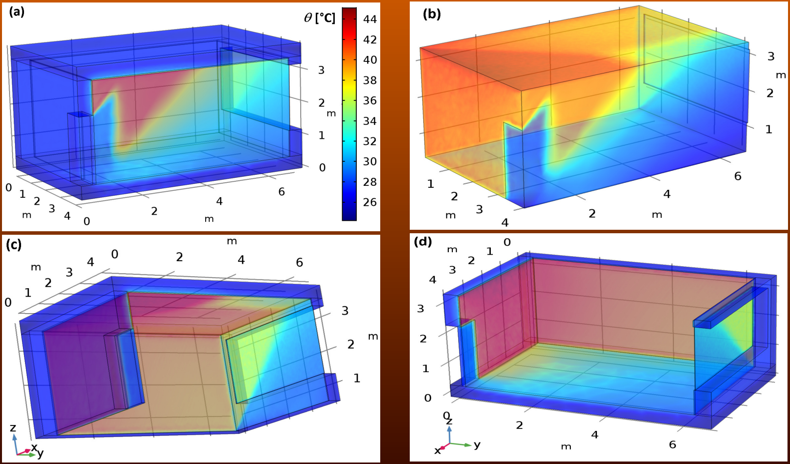
Differences of the air temperature inside the house

- Differences of the air temperature inside the house with the PCM coverage to the house without PCM coverage. Results for the house with wood wall thickness of (a) 0.2 m; (b) 0.3 m; (c) 0.4 m.



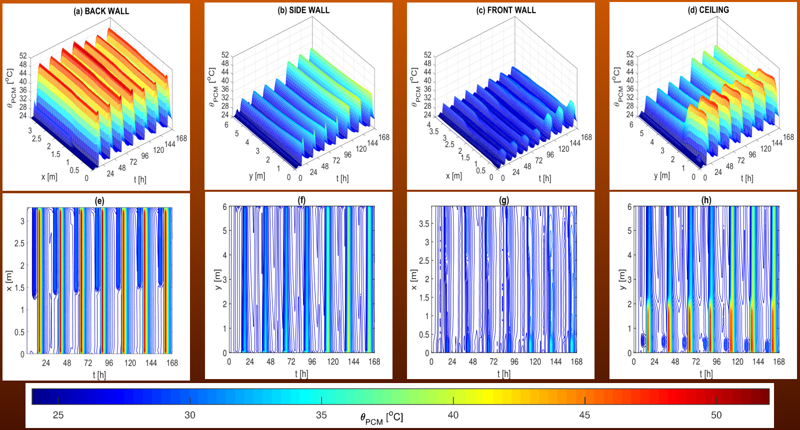
Temperature distribution in model *M2*

0.3 m wooden wall thickness covered by a PCM after 168 hours



Time evolutions of temperatures on PCM surfaces

Model *M*2 with the wood layer thickness of 0.3 m



Daily maximum and minimum temperature on the PCM surfaces (Wood layer thickness of 0.3 m)

Temperature [°C]

25	27	29	31	33	35	37	39	41	43	45	47	49	51

(a) MAXIMUM TEMPERATURE [°C]

PCM location	**D 1**	**D 2**	**D 3**	**D 4**	**D 5**	**D 6**	**D 7**
*M*2: Back wall	49.3	50.3	50.7	50.9	49.0	49.1	49.2
*M*2: Side wall	32.2	32.9	33.3	33.5	38.8	39.2	39.6
*M*2: Front wall	25.7	29.5	29.9	30.1	30.3	30.5	30.7
*M*2: Ceiling	33.8	34.6	35.0	35.2	40.4	40.7	40.9
*M*3: Back wall	47.8	48.8	49.2	49.4	49.1	49.4	49.5

(b) MINIMUM TEMPERATURE [°C]

PCM location	**D 1**	**D 2**	**D 3**	**D 4**	**D 5**	**D 6**	**D 7**
*M*2: Back wall	24.0	26.5	26.7	26.9	26.8	27.0	27.7
*M*2: Side wall	24.0	25.1	25.3	25.5	25.4	25.7	25.7
*M*2: Front wall	23.9	25.1	25.4	25.5	27.7	27.9	28.0
*M*2: Ceiling	24.0	25.3	25.7	25.8	25.8	26.0	26.1
*M*3: Back wall	24.0	26.5	26.7	26.9	26.8	27.0	27.0

Efficiency of the PCM coverage

Table: Efficiency of the PCM coverage.

WOOD THICK.	MODEL	EFFICIENCY OF PCM COVERAGE [%]						
		D 1	D 2	D 3	Day 4	D 5	D 6	D 7
0.2 m	*M2*	-	10.1	8.7	7.7	14.7	14.7	14.9
	M3	-	27.3	25.5	25.4	30.0	30.4	31.1
0.3 m	*M2*	-	11.4	11.1	9.4	17.8	16.5	15.9
	M3	-	22.0	28.5	27.4	30.5	29.0	29.1
0.4 m	*M2*	-	22.2	21.1	20.5	22.8	21.9	21.4
	M3	-	25.3	22.6	21.1	28.5	27.9	27.8

- The values represent the percentage decrease in air temperature in models *M*2 and *M*3 with the PCM, relative to the air temperature of model *M*1 without the CPM coverage.
- The values were compared at times when the air temperature inside the house reached a maximum for each simulated day.

Average daily temperature of the air inside the house and the range of temperature values

Table: Average daily temperature of the air inside the house and the range of temperature values.

WOOD THICKNESS	MODEL	(a) AVERAGE DAILY TEMPERATURE [$^\circ$C]						
		D 1	**D 2**	**D 3**	**D 4**	**D 5**	**D 6**	**D 7**
0.2 m	*M*1	26.1	27.1	27.4	27.5	28.2	28.4	28.5
	*M*2	26.0	27.5	28.1	28.3	28.6	28.8	28.9
	*M*3	25.5	26.8	27.3	27.5	28.0	28.2	28.2
0.3 m	*M*1	26.1	27.3	27.6	27.8	28.3	28.4	28.4
	*M*2	26.0	27.4	27.8	28.1	28.4	28.7	28.8
	*M*3	25.5	27.0	27.3	27.5	28.0	28.3	28.4
0.4 m	*M*1	26.5	27.6	27.8	27.8	28.4	28.7	28.7
	*M*2	26.1	27.5	27.9	28.1	28.4	28.7	28.8
	*M*3	25.6	27.3	27.8	28.2	28.3	28.5	28.6
WOOD THICKNESS	**MODEL**	**(b) RANGE OF TEMPERATURE VALUES [$^\circ$C]**						
		D 1	**D 2**	**D 3**	**D 4**	**D 5**	**D 6**	**D 7**
0.2 m	*M*1	8.7	7.9	7.9	7.9	10.6	10.4	10.6
	*M*2	7.4	6.5	6.3	6.3	7.8	7.8	7.9
	*M*3	6.0	5.3	5.1	5.0	6.2	6.1	6.2
0.3 m	*M*1	8.6	7.7	7.7	7.7	10.3	10.2	10.4
	*M*2	7.4	6.4	6.3	6.3	7.5	7.5	7.6
	*M*3	6.0	5.8	4.9	4.9	6.2	6.0	6.0
0.4 m	*M*1	9.8	8.9	8.9	8.9	10.5	10.4	10.5
	*M*2	7.2	6.2	6.1	6.1	7.1	7.1	7.1
	*M*3	5.9	6.3	6.1	6.1	6.2	6.2	6.2

Conclusions

Conclusions

- The PCM coverage can prevent an extreme increase in the air temperature in a house, especially in the afternoon and evening hours.
- For all of the studied models, the air temperature inside the house on each simulated day reached the highest values between approximately 4:00 and 6:00 PM, which corresponds to time courses of the outdoor air temperature and solar radiation intensity with regard to the time delay of thermal transfer through the walls and windows of the house.
- For the optimal efficiency of PCMs, it is necessary to perform a daily complete melt-freeze cycle.
- The maximum temperature decrease was 3.9 $^{\circ}\mathrm{C}$ (i.e. drop of 31.1%) comparing the house which wall opposite the window was covered by the PCM and the house without the PCM coverage.
- Results of the simulations did not confirm that the coverage of the PCM walls would significantly affect the average daily temperature of the air inside the house under the considered conditions.
- Testing the influence of PCMs on the thermal stability and thermal comfort inside buildings by computer simulations has allowed us to obtain basic information for further detailed assessment.
- There are a number of limitations that it is necessary to consider when performing computer simulations.

References

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