UDK 536.65:536.42
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 46(3)239(2012)

SIMULATION OF LATENT-HEAT THERMAL STORAGE INTEGRATED WITH ROOM STRUCTURES

SIMULACIJA HRANJENJA LATENTNE TOPLOTE, INTEGRIRANE V SOBNIH STRUKTURAH

Pavel Charvat[1], Tomas Mauder[1], Milan Ostry[2]

[1]Brno University of Technology, Faculty of Mechanical Engineering, Technicka 2896/2, 616 69 Brno, Czech Republic
[2]Brno University of Technology, Faculty of Civil Engineering, Veveri 331/95, 602 00 Brno, Czech Republic
charvat@fme.vutbr.cz

Prejem rokopisa – received: 2011-10-20; sprejem za objavo – accepted for publication: 2012-02-13

The phase change of a material is accompanied by a release or absorption of a considerable amount of heat. That makes a phase change a phenomenon effectively usable in various thermal storage applications. There are many materials with a melting temperature lying within the thermal comfort range for indoor environments. These materials can be utilized in building-integrated thermal storage. The performance of such latent-heat thermal storage integrated with the room structures was investigated through numerical simulations and experiments. The studied case involved two adjacent rooms of the same dimensions. The hydrated-salt-based phase-change material (PCM) was used as a thermal storage medium. A comparative approach was adopted in which the internal structures of one of the rooms contained the PCM, while the structures in the other room did not. The simulation model of the rooms was created in the numerical simulation tool TRNSYS 17, and this model was coupled with a PCM model created in MATLAB. The enthalpy method was used for the simulation of the phase change. This approach allowed for different time steps in the room model and the PCM model (the time step in the PCM model needed to be much shorter). The data from the real-scale experiments (ventilation rates, temperature of supply air, outdoor temperature, solar radiation intensity, etc.) as well as the physical properties of the PCM acquired in the laboratory testing were used as inputs to the simulation models. The analysis of the results was carried out, in which the simulation results were compared with the experimentally obtained data.

Keywords: latent-heat storage, phase-change materials, building simulations

Fazno spremembo materiala spremlja sproščanje ali absorpcija velike količine toplote. Zato je fazna sprememba pojav, ki se lahko na različne načine učinkovito uporablja s hranjenjem toplote. Obstaja več vrst materialov, ki imajo tališče v toplotnem razponu, ki velja za notranje prostore. Ti materiali se lahko uporabljajo v hranilnikih toplote, ki se integrirajo v konstrukcije. Številne numerične simulacije in eksperimenti so že bili izvedeni za ocenjevanje učinkovitosti takšnih hranilnikov latentne toplote, ki so integrirani v sobne strukture. Obravnavani primer je vključeval dva sosednja prostora enakih dimenzij. Fazno spremenljiv material (PCM), ki temelji na hidratirani soli, je bil uporabljen kot sredstvo shranjevanja toplote. Uporabljen je bil primerjalni način, pri katerem so notranje strukture v enem prostoru vsebovale PCM, medtem ko ga strukture v drugem prostoru niso. Simulacijski model prostorov je bil izveden z orodjem za simulacije TRNSYS 17, ta model pa je bil združen z modelom PCM, ki je bil ustvarjen v laboratoriju MATLAB. Za simulacijo fazne spremembe je bila uporabljena metoda entalpije. S tem načinom je bilo mogoče ustvariti stopnje v prostorskem modelu in modelu PCM z različnimi časovnimi dimenzijami (časovna stopnja v modelu PCM je morala biti znatno krajša). Podatki, ki so bili pridobljeni iz eksperimentov v realnem stanju (razmerja prezračevanja, temperatura dovodnega zraka, zunanja temperatura, intenzivnost sončnega sevanja itd.), ter fizične lastnosti materialov PCM, ki so bili pridobljeni pri laboratorijskih preizkusih, so bili uporabljeni kot vhodni podatki za simulacijske modele. Izvedena je bila analiza podatkov, kjer so se rezultati simulacije primerjali s podatki, pridobljenimi med eksperimenti.

Ključne besede: hranjenje latentne toplote, fazno spremenljivi materiali, simulacija gradnje

1 INTRODUCTION

The increasing demand for energy conservation and thermal comfort in built environments has led to the study of new approaches and materials in building construction. Thermal storage integrated with building structures can contribute to energy conservation in buildings through the reduction of peak cooling or heating loads. The phase change of a material is accompanied by the release or absorption of a considerable amount of heat and that makes such a phase change a phenomenon that is effectively usable in various thermal storage applications. Many materials or their mixtures have a melting temperature in the thermal comfort range of built environments. Advances in materials science and chemistry have allowed for fine-tuning of the material properties for the specific applications. The use of phase-change materials (PCMs) in building structures has been the subject of considerable interest in the past decade. This interest is documented by numerous papers that address this issue.[1–3]

2 EXPERIMENTAL SET-UP

The studied case involves two adjacent rooms of the same dimensions and geometry. A comparative approach was adopted in which the internal structures of one of the rooms contained the PCM, while the structures in the other room did not. A schematic view of the rooms can be seen in **Figure 1**.

The aluminum containers with DELTA®-COOL24 PCM were installed in one of the rooms. The dimensions of the containers are 455 mm × 305 mm × 10 mm. The naked aluminum containers filled with a PCM represent

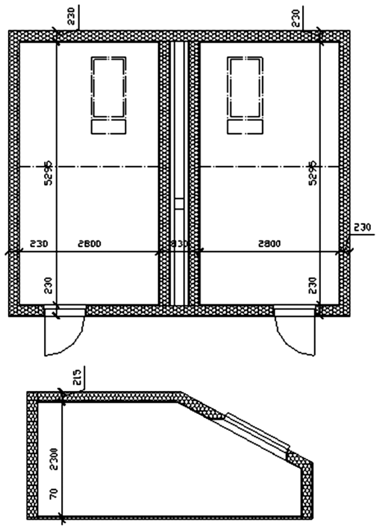

Figure 1: Experimental rooms
Slika 1: Eksperimentalni prostori

one of the best thermal storage options in terms of heat transfer and heat-storage density per unit of surface area. Each container accommodated about 1.1 kg of the PCM with a thermal capacity of 150 kJ/kg in the melting range between 22 °C and 28 °C. This represented a thermal storage capacity of over 1 MJ/m^2 in the indicated temperature range.

The compositions of the multi-layer walls of the test rooms are shown in **Figure 2**. The thermo-physical properties of the wall materials needed for the simulation (such as thermal conductivity, density, specific heat capacity) were obtained from the Czech national standard ČSN 73 0540-3 and they are summarized in **Table 1**.

Table 1: Thermo-physical properties of the wall materials
Tabela 1: Toplotno-fizikalne lastnosti stenskih materialov

Material	ρ/(kg/m^3)	c/(J/(kg K))	k/(W/m K)
Plaster-board	750	1060	0.22
Mineral wool	300	880	0.079

Table 2: Thermo-physical properties of the PCM
Tabela 2: Toplotno-fizikalne lastnosti fazno spremenljivih materialov

PCM	ρ/(kg/m^3)	c/(J/(kg K)	k/(W/mK)
Solid	1600	2700	1.12
Liquid	1500	2200	0.56
Melting range	22–28 °C		
Melting energy	158 kJ/kg		

The thermo-physical properties of the DELTA®-COOL24 PCM, as stated by the manufacturer, are in **Table 2**.

The thermo-physical properties of the PCM were also investigated by means of differential scanning calorimetry with the use of the Q200 calorimeter. The obtained melting range was approximately 20–30 °C with an evaluated thermal capacity of 166 kJ/kg in that range.

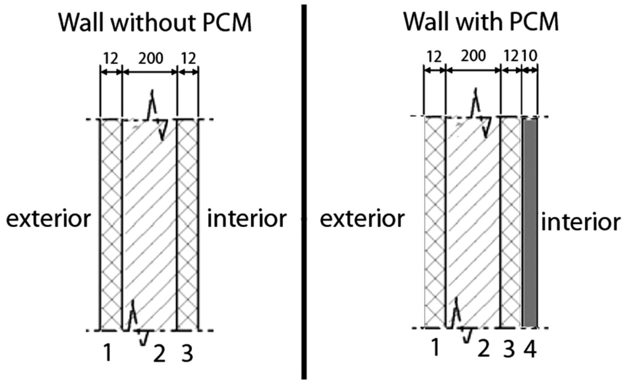

Figure 2: Composition of the walls: (1, 3) plasterboard, (2) mineral wool, (4) PCM
Slika 2: Sestava sten: (1, 3) mavčne plošče, (2) mineralna volna, (4) PCM

The samples used for DSC testing are rather small, which is a problem because the PCM is a mixture of several substances and such a small sample may not have the same composition as a much larger volume of the PCM in the container. Moreover, the thermo-physical properties of the hydrated-salt PCMs are very sensitive to moisture content, which can change during the acquisition and testing of the sample. The heat flux vs. temperature plot obtained by differential scanning calorimetry is shown in **Figure 3**.

The experimental and numerical results presented in this paper correspond to a time period of 2 weeks in the summer of 2009 (between August 11 and August 24). The experiments took place at the Faculty of Civil Engineering in the city of Brno in the Czech Republic. The data obtained from the test-room experiments were used as the inputs for the numerical simulations (ventilation rates, temperature of supply air, outdoor temperature, solar radiation intensity).

3 MATHEMATICAL MODEL AND SIMULATION

The above-described case of latent-heat storage in building structures was numerically simulated with the

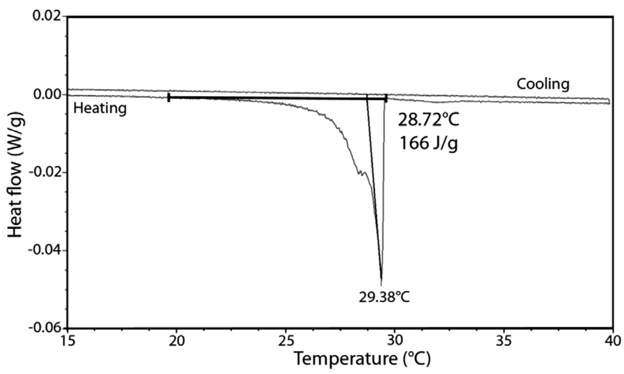

Figure 3: Heat flux vs. temperature plot obtained by DSC
Slika 3: Toplotni tok v primerjavi s temperaturnim razponom, pridobljenim z DSC

use of coupling between the TRNSYS (Transient System Simulation tool) and MATLAB. The simulated problem can be classified as transient heat transfer involving a phase change. Over the years, a number of related computational works have employed various techniques in the analysis of phase-change problems.[4,5] Most analytical solutions dealing with 1-D geometries for very particular sets of boundary conditions cannot be generalized to more complex problems. With the introduction of high-speed digital computers for mathematical modeling, the numerical simulations have become quite an economical and fast approach to solving many engineering problems. The phase-change problem can be solved by a numerical analysis that involves either the finite-difference or the finite-element methods. The finite-difference method was used in the simulations described in this paper. The phase change was modeled with the use of the latent-heat-accumulation approach that is sometimes referred to as the enthalpy method. In the basic enthalpy scheme, the enthalpy is used as the primary variable and the temperature is calculated from a defined enthalpy-temperature relation[6]:

$$H=\int_0^T\left(\rho(\xi)c(\xi)-\rho(\xi)\Delta H\frac{\partial f_s}{\partial T}\right)\mathrm{d}\xi \tag{1}$$

where H/(J/m^3) is the volume enthalpy, ΔH/(J/kg) is the latent-heat coefficient, ρ/(kg/m^3) is the density, c/(J/kg K) is the specific heat capacity and f_s/(–) is the solid fraction.

A 1-D model of the multi-layer wall with an interior layer containing the PCM (**Figure 2**) was created in MATLAB. The 1-D simplification seemed to be justified by the assumption of uniform boundary conditions over the entire surface of the wall on each side. The temperature distribution in the wall can be obtained from the Fourier equation, which for the 1-D case reads as[3–5]:

$$\frac{\partial H}{\partial \tau}=k(T)\frac{\partial^2 T}{\partial x^2} \tag{2}$$

where k/(W/m K) is the thermal conductivity, T/K is the temperature, τ/s is the real time and x/m is the space coordinate.

The finite-difference method was used to solve the Fourier equation. The continuous information contained in the exact solution of the differential equation is replaced by the discrete temperature values T_i^n in the numerical solution. The subscript i concerns the space coordinate and the superscript n is the time coordinate. The explicit finite-difference scheme according to the enthalpy method with the non-equidistant space steps is:

$$H_i^{n+1}=H_i^n+\Delta\tau k(T)\left(\frac{\dfrac{T_{i+1}^n-T_i^n}{\Delta x_i}-\dfrac{T_i^n-T_{i-1}^n}{\Delta x_{i-1}}}{\dfrac{\Delta x_i-\Delta x_{i-1}}{2}}\right) \tag{3}$$

The initial and boundary conditions for the equations (2) and (3) must be provided. The initial condition describes the initial temperature distribution in the multi-layer wall and it was obtained from the measurement in the studied case.

The model of the test rooms was created in the TRNSYS tool and this model was coupled with the described model of the multi-layer wall created in MATLAB. The air temperature in the room obtained from TRNSYS was used as a boundary condition for the heat transfer at the wall, which was handled by the MATLAB model, and the wall surface temperature from MATLAB was returned to the TRNSYS as a boundary condition for the next time step. A time step of 60 seconds was used in the TRNSYS model, while the MATLAB model used a much shorter time step of 1 s (to address the phase change properly). The communication between MATLAB and TRNSYS was provided through the TRNSYS type 155.

The stability condition for the explicit formula was used according to the unconditionally stable fully

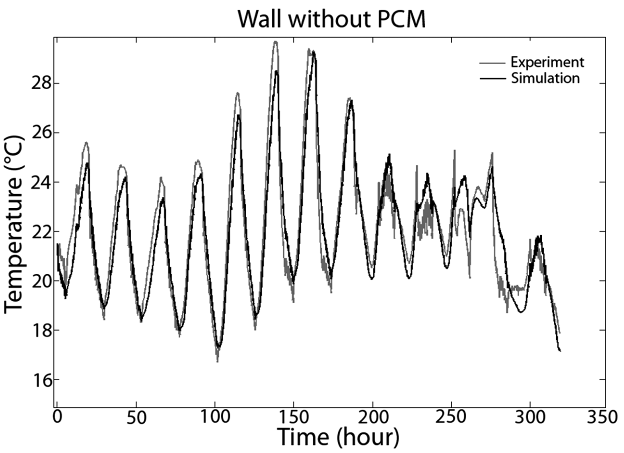

Figure 4: Measured and simulated temperatures in room 1
Slika 4: Izmerjene in simulirane temperature v prostoru 1

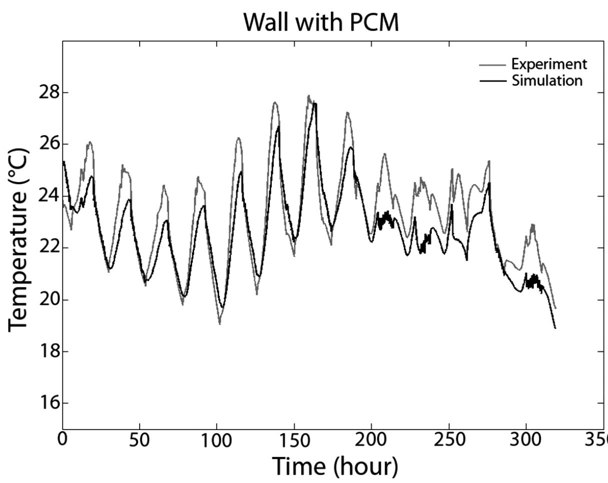

Figure 5: Measured and simulated temperatures for room 2
Slika 5: Izmerjene in simulirane temperature v prostoru 2

explicit finite-difference solution of the solidification problems.[5]

4 RESULTS AND DISCUSSION

The experimental data was available in 15-minute intervals, while the simulations were performed with a time step of 1 min. The experimental data was re-sampled to the simulation time step using the quadratic interpolation in order that the data could be used as boundary conditions for the simulations.

The results of the simulation for the experimental room without the PCM compared with the experimentally obtained data can be seen in **Figure 4**. The chart shows a relatively good agreement of the simulated and measured room temperatures. The maximum difference between the measured and simulated temperature was 1 °C.

The results for the experimental room with the walls containing the PCM are shown in **Figure 5**. The maximum difference between the measured and simulated temperature is 2.5 °C. There can be several explanations for this discrepancy. The uniform boundary condition (air temperature, heat-transfer coefficient) was applied to the entire surface of the walls containing the PCM in the numerical model. The distribution of the heat-transfer coefficient over the wall surface was not thoroughly investigated in the experiment. Also, the heat-transfer case was assumed to be 1-D with the heat flux in the direction of the normal to the surface of the wall. The observations made in the experimental room indicated that the melting and solidification of the PCM in the containers was not uniform with pockets of solid PCM at the bottom of the containers (separation due to gravity).

If we compare the temperatures in the experimental room (**Figures 4** and **5**) we can see that the presence of the PCM reduces the air-temperature fluctuations in the room. This reduction can improve the thermal comfort of the occupants, which corresponds with the findings of other authors[3].

5 CONCLUSION

A numerical model of a multi-layer wall containing a phase-change material was developed. This model was coupled with the TRNSYS simulation tool and employed for the simulation of experiments that were carried out in the experimental rooms. A good agreement was achieved between the simulation results and the experimental data in terms of the general trends. However, the simulation model was not always able to predict the indoor temperature with an accuracy necessary for practical applications. Further development of the model is in progress. Both the experimental investigations and the numerical simulations showed that the phase-change material integrated with the wall structure attenuated the air-temperature fluctuations in the room.

Acknowledgement

The authors gratefully acknowledge the financial support from the project OC10051 of the Czech Ministry of Education and the project ED0002/01/01 – NETME Centre, and the Junior Research Project on BTU BD13102003.

6 REFERENCES

[1] R. Baetens, P. B. Jelle, A. Gustavsen, Phase change materials for building applications: A state-of-the-art review, Energy and Buildings, 42 (**2010**) 9, 1361–1368

[2] V. Butala, U. Stritih, Experimental investigation of PCM cold storage, Energy and Buildings, 41 (**2009**) 3, 354–359

[3] F. Kuznik, J. Virgone, J. Roux, Energetic efficiency of room wall containing PCM wallboard: A full-scale experimental investigation, Energy and Buildings, 40 (**2008**) 2, 148–156

[4] M. Muhieddine, É. Canot, R. March, Various approaches for solving problems in heat conduction with phase change, International Journal on Finite Volumes, 6 (**2009**) 1, 20

[5] R. Tavakoli, P. Davami, Unconditionally stable fully explicit finite difference solution of solidification problems, Metallurgical and Materials Transactions B, 38 (**2007**) 1, 121–142

[6] F. Kavička, J. Stetina, B. Sekanina, K. Stransky, J. Dobrovska, J. Heger, The optimization of a concasting technology by two numerical models, Journal of Materials Processing Technology, 185 (**2007**) 1–3, 152–159