ZESZYTY NAUKOWE POLITECHNIKI RZESZOWSKIEJ Nr 271
Budownictwo i Inżynieria Środowiska z. 57 (4/10) 2010

Elżbieta KOSSECKA, prof. dr hab.

Instytut Podstawowych Problemów Techniki PAN
Zakład Problemów Eko-Budownictwa
Ul. Świętokrzyska 21, 00-049 Warszawa
e-mail: ekossec@ippt.gov.pl

Jan Kośny, dr inż.

Oak Ridge National Laboratory
Buildings and Materials Group; Bldg. 3247, M.S. 6070
Oak Ridge; TN 37831-6070, USA
e-mail: kyo@ornl.gov

DYNAMIC THERMAL PERFORMANCE OF THE FRAME WALL WITH PCM-ENHANCED THERMAL INSULATION

ABSTRACT

Simulations have been carried out to demonstrate the performance of a light-weight wall assembly with PCM-enhanced insulation in different external climate thermal conditions. Weather data of Typical Meteorological Year (TMY) for the hot period of 30 June through 3 July, for three locations: Warsaw, Marseille and Cairo, were used to generate boundary conditions at the external surface of the south-oriented vertical wall. For internal temperature of 24oC, heat gains maxima are reduced by 23% to 37% for Marseille and 21% to 25% for Cairo; similar effects are to be observed for Warsaw.

1. INTRODUCTION

Different types of Phase Change Materials (PCMs) have been tested as dynamic components in buildings during the last 4 decades. Most historical studies have found that PCMs enhance building energy performance. Some PCM-enhanced building materials, like PCM-gypsum boards or PCM-impregnated concretes have already found their limited applications in different countries. Today, continued improvements in building envelope technologies suggest that throughout Southern and Central US climates, residences may soon be routinely constructed with PCM in order to maximize insulation effectiveness and maintain low heating and cooling loads.

During the late 1980s and early 1990s, Oak Ridge National Laboratory (ORNL) tested several configurations of gypsum boards enhanced with phase-change materials (PCMs) and in 2002, an ORNL research team started working on fiber insulations blended with microencapsulated PCMs, produced with the use of a new micro-encapsulation technology that holds microscopic wax droplets inside hard acrylic polymer shells.

These PCM–insulation mixtures function as lightweight thermal mass components. It is expected that these types of dynamic insulation systems will contribute to the objective of reducing energy use in buildings and to the development of "zero-net-energy" buildings. This is a consequence of this technology's ability to reduce energy consumption for space conditioning and reshape peak-hour loads. Other anticipated advantages of PCMs include improvements towards occupant comfort, compatibility with traditional wood and steel framing technologies, and potential for application in retrofit projects. ORNL research demonstrated that PCMs can be mixed with fiber insulations, incorporated into structural and sheathing materials, or packaged for localized application. Results from a series of small-scale laboratory measurements and field experiments indicate that a new generation of PCM-enhanced fiber insulations could have excellent potential for successful application in U.S. buildings because of their ability to reduce energy consumption for space conditioning and reduce peak loads [7, 8, 9, 10].

New PCM applications require a careful selection of materials, identification of PCM locations, bounding of thermal resistances, and specification of the amount of PCM to be used [1, 2, 6, 15]. The major goal of this work was numerical analysis of the energy performance of the frame wall with PCM-enhanced insulation in different climate conditions.

2. HEAT TRANSFER THROUGH A WALL WITH PCM

The estimated area heat storage capacity for a specific PCM-enhanced product is a key indicator of its future dynamic thermal performance. A theoretical model of the material with temperature-dependent specific heat can be used to calculate phase change processes in most common materials [1, 4, 6, 13]. The one-dimensional heat transport equation for such a case is:

$$\frac{\partial}{\partial t}(\rho h)=\frac{\partial}{\partial x}\left[\lambda\frac{\partial T}{\partial x}\right]\ , \tag{1}$$

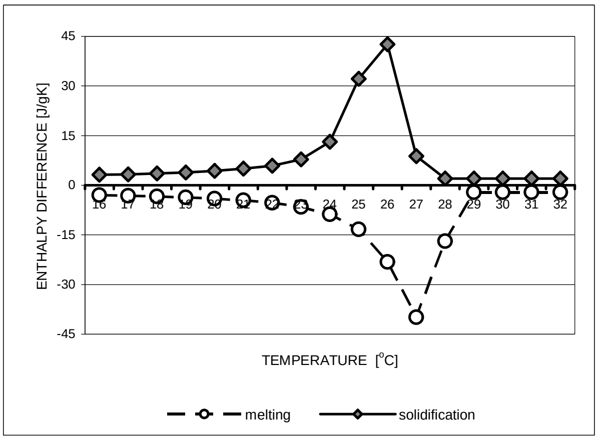
where ρ and λ are the material density and thermal conductivity, whereas T and h are temperature and enthalpy per unit mass.

The enthalpy derivative over the temperature (with consideration of constant pressure) represents the effective heat capacity, with phase change energy being one of the components:

$$c_{eff}=\frac{\partial h}{\partial T}\ . \tag{2}$$

For most PCM materials, variations of enthalpy with temperature depend to some extent on the direction of the process considered, and are different for melting and solidification. Therefore a model of the temperature-dependent specific heat, represented by an unique function of temperature, is an approximation of a real material thermal capacitance.

Figure 1 depicts temperature-dependent enthalpy differences and enthalpy curves for microencapsulated PCM, generated during differential scanning calorimeter testing. In this material, the melting takes place around 27°C and solidification around 26°C. Total phase change enthalpy, H_m, within temperature interval [20°, 29°] is 122 kJ/kg.



Rys. 1. Dane kalorymetryczne PCM w postaci mikrokapsułek
Fig. 1. Calorimetric data for the microencapsulated PCM

Effective heat capacity, c_{eff}, for a material which is a blend of insulation and PCM may be expressed as

$$c_{eff} = (1-\alpha)c_{ins} + \alpha c_{effPCM} \ , \tag{4}$$

where α denotes the percentage of PCM, c_{ins} the specific heat of insulation without PCM and c_{effPCM} is effective heat capacity of PCM.

In the liquid state, the effective heat capacity of PCM doesn't show temperature dependence; it may be thus represented as the sum of two terms:

$$c_{effPCM}(T) = c_l + \left(c_{effPCM}(T) - c_l\right), \tag{5}$$

where c_l represents the temperature independent specific heat in the liquid state.

For a material to be used as thermal insulation, thermal conductivity is the most important parameter, which determines its thermal performance in different thermal conditions. For cellulose fiber insulation, linear dependence of conductivity on temperature is to be observed [9, 10]:

$$\lambda(T) = \lambda_0 + \beta \cdot T \tag{6}$$

$$\lambda_0 = 0.03575; \qquad \beta = 0.00013$$

Addition of microencapsulated PCM does not result in a significant change in conductivity of the insulation.

Consider a plane wall of thickness L, composed of layers of different materials, and assume that some of them are phase change materials. Boundary (linear) conditions at the internal ($x = 0$), and external ($x = L$) surface of the wall have the form:

$$q(0,t) = \frac{1}{R_{si}}\left[T_i(t) - T(0,t)\right] \tag{7}$$

$$q(L,t) = \frac{1}{R_{se}}\left[T(L,t) - T_e(t)\right] \tag{8}$$

where T_i and T_e are ambient temperatures and R_{si}, R_{se}, surface film resistances.

Denote by $R_{i\text{-}x}$ and $R_{x\text{-}e}$ the resistances for heat transmission from the point x in the wall to the internal and external environment, respectively, and by R_u the total resistance for heat transmission through the wall. With conductivity along the wall's thickness is represented by the function $\lambda(x)$, the resistances are given by:

$$R_{i-x} = R_{si} + \int_0^x \frac{dx}{\lambda(x)} \qquad R_{x-e} = \int_x^L \frac{dx}{\lambda(x)} + R_{se} \qquad R_u = R_{si} + \int_0^L \frac{dx}{\lambda(x)} + R_{se} \tag{9}$$

Multiplying of Eq. (1) by the function $R_{x\text{-}e}$ and integrating with respect to x over thickness of the wall, yields the following formula:

$$\int_0^L \rho \cdot \frac{\partial h}{\partial t} \cdot R_{x-e}\, dx = \int_0^L \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) \cdot R_{x-e}\, dx = \left(\lambda \frac{\partial T}{\partial x}\right) \cdot R_{x-e}\Bigg|_{x=0}^{x=L} + \int_0^L \frac{\partial T}{\partial x} dx =$$

$$= -R_{se} \cdot q(L) + R_{0-e} \cdot q(0) + \left[T(L) - T(0)\right] \tag{10}$$

Temperatures T(0) and T(L) may be eliminated using Eqs (7) and (8), which gives the following formula for the heat flux at internal surface:

$$q(0) = \frac{1}{R_u}(T_i - T_e) + \int_0^L \rho \frac{\partial h}{\partial t} \cdot \frac{R_{x-e}}{R_u} dx \tag{11}$$

Analogous formula for $q(L)$ is to be obtained on multiplying Equation (1) by $R_{i\text{-}x}$ and integrating by parts [11].

The effect of time variations of enthalpy h along thickness of the wall, on the heat flux across the surface $x = 0$, depends thus on the factor $R_{x\text{-}e}/R_u$, which takes comparatively high values, close to 1, in the vicinity of that surface and low values, close to 0, in the vicinity of the opposite surface $x = L$. This means that only time variations of enthalpy near the surface considered play an important role, whereas the effect of variations near the opposite surface may be small.

2. PERFORMANCE OF THE FRAME WALL WITH PCM-ENHANCED INSULATION IN DIFFERENT CLIMATE CONDITIONS

Simulations have been carried out to demonstrate the performance of a light-weight wall assembly with PCM-enhanced cellulose fiber insulation in different external climate thermal conditions. The "melting curve" of Figure 1 has been assumed as a model of the PCM effective heat capacity. Temperature dependence of thermal conductivity was represented by Eq (6).

Wall assembly similar to a typical 14 cm (5.5 in) wood frame wall has been considered. One-dimensional heat transfer has been assumed and the effect of studs has been neglected. Thermophysical properties of the wall's layers are listed in Table 1. Approximate value of total resistance for heat transfer, R_u, calculated assuming constant insulation conductivity value $\lambda(25°C)$ = 0.039 W/(m·K), including surface film resistances R_{si} = 0.13 m²·K/W and R_{se} = 0.04 m²·K/W, is 4.14 m²·K/W, and U-value is 0.24 W/(m²·K). PCM content of 30% in an insulation layer of thickness of 0.14 m and density of 33.6 kg/m³ means about 1.4 kg of PCM per square meter of a wall.

Tabela 1. Własności termofizyczne warstw ściany
Table 1. Thermophysical properties of the wall's layers

Material	L m	λ W/(m·K)	ρ kg/m³	c_p kJ/(kg·K)
Gypsum board	0.013	0.16	800	1.088
Insulation	0.140	λ(T)	25.6	1.381
Ins. 30% PCM	0.140	λ(T)	33.6	c_p(T)
Plywood	0.013	0.12	544	1.244
Wood siding	0.013	0.07	545	1.255

Weather data of Typical Meteorological Year (TMY) [3, 5, 14], for the hot period of 30 June through 3 July, for three locations: Warsaw, Marseille and Cairo, were used to generate boundary conditions at the external surface of the wall. Solar radiation for each location was calculated for a vertical plane oriented south. Internal temperature, T_i, has been set constant at 24°C, at the same time.

In the linear model, when the heat flux due to solar radiation absorbed at the wall's surface, q_s, is included, boundary condition (7) takes the form:

$$q(L)=\frac{1}{R_{se}}\left[T(L)-T_e\right]-q_s=\frac{1}{R_{se}}\left[T(L)-T_{es}\right] \quad (12)$$

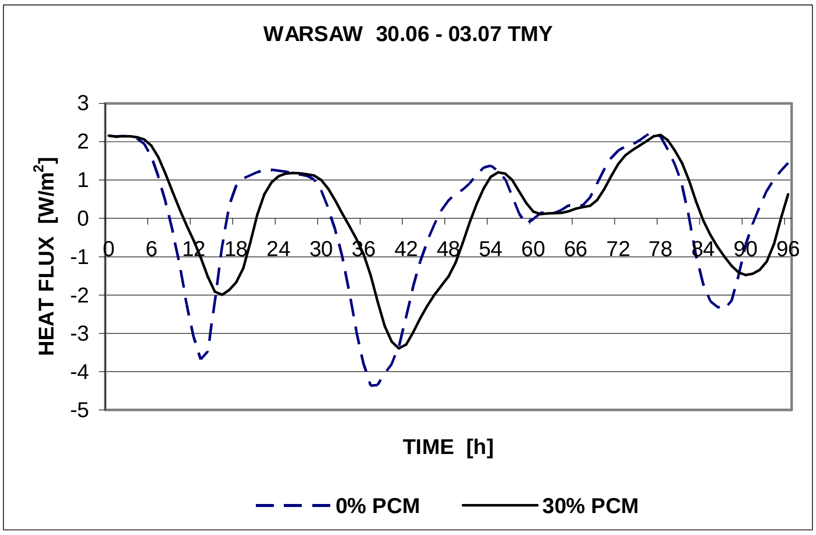
$$T_{es}=T_e+R_{se}\cdot q_s \quad (13)$$

T_{es} is the so called sol-air temperature. With R_{se} = 0.04 m²·K/W and absorption coefficient of 0.8, solar radiation flux of 1000 W/m² increases T_{es} by 32°C.

Figures 2, 3 and 4 show comparison of heat flux profiles for subsequent four days, at internal surfaces of two walls; one containing the normal fiber insulation layer, and another one containing PCM-enhanced insulation, with 30% of PCM by weight.

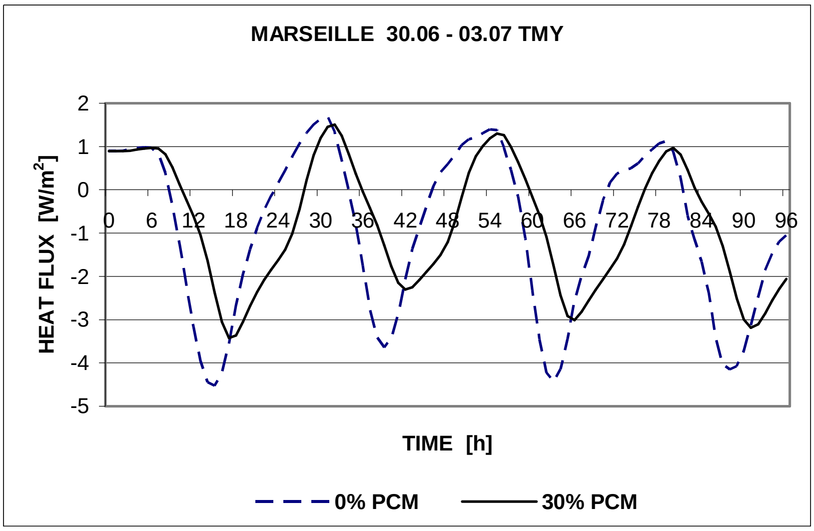
Comparison of the plots and calculated heat flow values indicates that for approximately cyclic processes the effect of PCM in an insulation layer results in time shifting and reduction of the heat flow rates extreme values but not in reduction of the total heat flow. Heat losses corresponding to minimum external temperatures at midnight are shifted to morning time, at the same time large heat gains from midday are shifted by about three hours to the afternoon time.

For T_i = 24°C the heat gains maxima are reduced by 23% to 37% for Marseille and 21% to 25% for Cairo. For Warsaw, which has more temperate climate, with less solar radiation, oscillations of the heat fluxes through walls are not as regular as for Cairo and Marseille, however the effect of reduction of heat gains maxima and time shifting looks more or less the same.



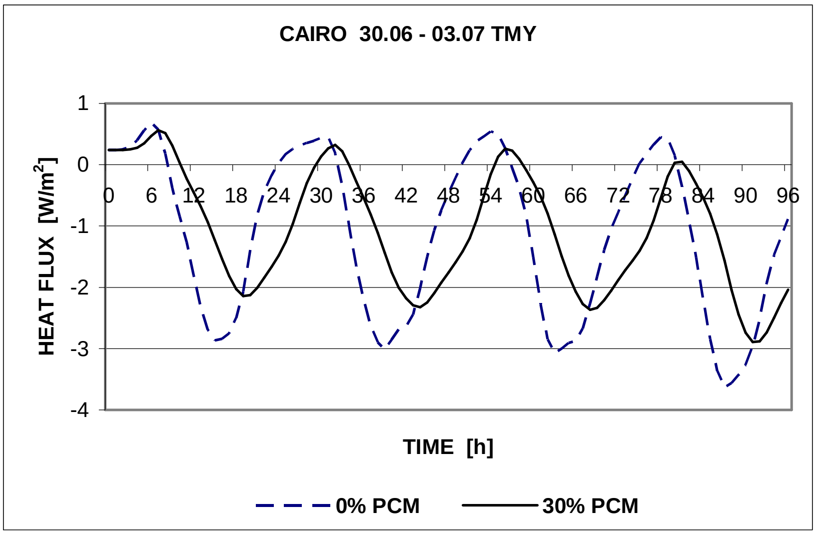
Rys. 2. Strumienie ciepła na wewnętrznej powierzchni ściany z warstwą izolacji o grubości 0.14 m bez PCM i z 30% PCM. Dane pogodowe TRM dla Warszawy; T_i = 24oC.

Fig. 2. Heat flux profiles at the internal surface of the wall containing 0.14 m thick insulation layer with 0% PCM and 30% PCM. Weather data: Warsaw TMY; T_i = 24oC.



Rys. 3. Strumienie ciepła na wewnętrznej powierzchni ściany z warstwą izolacji o grubości 0.14 m bez PCM i z 30% PCM. Dane pogodowe TRM dla Marsylii; T_i = 24oC.

Fig. 3. Heat flux profiles at the internal surface of the wall containing 0.14 m thick insulation layer with 0% PCM and 30% PCM. Weather data: Marseille TMY; T_i = 24oC.



Rys. 4. Strumienie ciepła na wewnętrznej powierzchni ściany z warstwą izolacji o grubości 0.14 m bez PCM i z 30% PCM. Dane pogodowe TRM dla Kairu; T_i = 24oC.
Fig. 4. Heat flux profiles at the internal surface of the wall containing 0.14 m thick insulation layer with 0% PCM and 30% PCM. Weather data: Cairo TMY; T_i = 24oC.

4. CONCLUSIONS

Results of simulations are consistent with results of theoretical considerations presented in section 2. Comparison of the plots and calculated heat flow values indicates that for approximately cyclic processes the effect of PCM in an insulation layer results in time shifting and reduction of the heat flow rates extreme values but not in reduction of the total heat flow.

For south oriented vertical frame walls, filled with PCM-enhanced insulation of thickness of 0.14 m, with PCM content of 30%, time shift of the heat flow rate oscillations is about three hours, compared to normal cellulose fiber insulation, and reduction of the heat gains maxima may be about 20% - 35% for hot and sunny Summer days, when air-conditioning is necessary.

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DYNAMICZNE WŁASNOŚCI CIEPLNE ŚCIAN Z IZOLACJĄ WZBOGACONĄ MATERIAŁEM FAZOWO-ZMIENNYM

STRESZCZENIE

Przeprowadzono symulacje, których celem było zbadanie dynamicznych własności cieplnych lekkich ścian szkieletowych z izolacją wzbogaconą materiałem fazowo-zmiennym, w różnych warunkach klimatycznych. Wykorzystane zostały dane pogodowe Typowego Roku Meteorologicznego dla gorącego okresu od 30 czerwca do 3 lipca, dla trzech lokalizacji: Warszawa, Marsylia i Kair. Przy temperaturze wewnętrznej 24oC, maksima zysków cieplnych dla pionowej ściany o orientacji południowej są zredukowane od 23% do 37% dla Marsylii i od 21% do 25% dla Kairu; podobne efekty można zaobserwować dla Warszawy.