Influence of PCMs in thermal insulation on thermal behaviour of building envelopes

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Abstract. A model of heat transfer through a wall consisting of a layer of concrete and PCM enhanced thermal insulation is considered. The model accounts for heat conduction in both layers, thermal radiation and heat absorption/release due to phase change in the insulation as well as time variation in the ambient temperature and insolation. Local thermal equilibrium between encapsulated PCM and light-weight thermal insulation was assumed. Radiation emission, absorption and scattering were also accounted for in the model. Comparison of different cases of heat flow through the building envelope was carried out. These cases included presence or absence of PCM and thermal radiation in the insulation, effect of emissivity of the PCM microcapsules as well as an effect of solar radiation or its lack on the ambient side of the envelope. Two ways of the PCM distribution in thermal insulation were also considered. The results of simulations were presented for conditions corresponding to the mean summer and winter seasons in Warsaw. It was found that thermal radiation plays an important role in heat transfer through thermal insulation layer of the wall while the presence of the PCM in it significantly contributes to damping of temperature fluctuations and a decrease in heat fluxes flowing into or lost by the interior of the building. The similar effect was observed for a decrease in emissivity of the microcapsules containing PCM.

1. Introduction

Heat losses or gains by building envelopes contribute to the increased energy consumption. In order to reduce energy demand materials having low values of thermal conductivity are used. Due to time variation in the ambient conditions envelopes should also have high heat capacity. Nowadays the buildings are characterized by thin walls separating the interior of the building from the ambient air and even when they are covered with thermal insulations of high quality and low density they lack sufficient heat capacity [1].

One of the ways to increase heat capacity of the building envelopes is to use phase change materials (PCMs). The phase change process involves a large amount of energy accumulated or released at a constant temperature or a narrow range of temperatures [2]. Both of these features are attractive for heating, cooling, and temperature stabilization purposes. PCMs have found applications in a wide range of areas including thermal energy storage [3], building energy efficiency, food product cooling, spacecraft thermal systems, solar power plants, microelectronics [4], thermal protection and...
waste heat recovery. In the case of buildings these materials have been tested as a thermal mass component for more than 40 years. Many potential PCMs were used including inorganic salt hydrates, organic fatty acids and eutectic mixtures, fatty alcohols, neopentyl glycol, and paraffinic hydrocarbons [5]. It was found that PCMs improve building energy performance by significantly reducing peak loads and shifting peak-demand time [6]. Therefore PCMs are expected to assist in development of “zero-net energy” buildings.

PCMs in buildings can assume different form and be located in different locations in the envelope. The studies focused on impregnating concrete, gypsum, or ceramic masonry or blending micro-encapsulated PCMs in building materials [7, 8]. The micro-encapsulation technology holds microscopic wax droplets inside hard acrylic polymer shells.

Some problems such as high initial cost, toxic behaviour, loss of phase change capability, corrosiveness (some inorganic PCMs) and PCM leaking have hampered widespread adoption of PCMs in buildings. Some of the PCMs (paraffinic hydrocarbons) also relatively cheap and having high heat capacity were at the same time found highly flammable. In the former applications, the chosen locations for flammable paraffinic PCMs were the interior surfaces of the wall, ceiling, or floor. Subsequent research demonstrated that the micro-encapsulated PCMs can be mixed with fibre insulations, incorporated into structural and sheathing materials, or packaged for localized application. These locations are expected to significantly reduce flammability problems [9]. One of the first successful developments was PCM-enriched cellulose. Studies concentrated an effect of the PCM content in the insulation and its capability of heat accumulation were also carried out [10]. These studies were followed by development of PCMs blended with blown fiberglass and plastic foams.

Theoretical predictions of PCMs applications in buildings envelopes were often presented in literature [11, 12, 13] but studies devoted to their use in thermal insulations are sparse and only account for heat conduction and phase change processes [14]. It is however known that thermal radiation can be an important mode in the light-weight fibrous insulations. The study on an impact of external solar radiation as well as thermal radiation within thermal insulation on heat losses or gains from building envelopes containing PCM-enriched insulation is the main topic of the present paper.

2. Heat transfer through a building envelope

2.1. Statement of the problem and ambient conditions

Two-layer building envelope directed southward was considered. The inner layer was made from a 24 cm thick aerated concrete, while the second layer was a 12 cm thermal insulation made from mineral wool, which can be enhanced with the encapsulated PCM uniformly spread across part or whole of its thickness. The internal space of the building was kept at constant temperature of $T_i(t) = 24^\circ C$, corresponding to the thermal comfort. The ambient conditions were assumed to vary not only with time but also with the season of a year. Both ambient temperature and insolation flux were determined on the basis of data obtained from the Polish Institute of Meteorology and Water Management – table 1 and 2. The ambient temperature was approximated by the formula:

$$T_a(t) = T_{av} + A \sin \omega t$$

where: $T_{av}$ – mean temperature during the season, $A$ – temperature amplitude during the season, $\omega = 2\pi/\tau$, with the period $\tau$ corresponding to 24 hrs.

The amplitude of temperature variation was averaged over five years period. It was determined using extreme temperatures, which differed by 5% from the lowest and highest temperature in the respective season.
Table 1. Mean temperature in Warsaw neighbourhood in the years 2010-14 [15].

| Season | Year | 2010 [°C] | 2011 [°C] | 2012 [°C] | 2013 [°C] | 2014 [°C] | Mean [°C] |
|--------|------|-----------|-----------|-----------|-----------|-----------|-----------|
| Spring |      | 9         | 8         | 10        | 9         | 11        | 9         |
| Summer |      | 20        | 19        | 20        | 19        | 18        | 19        |
| Fall   |      | 9         | 9         | 10        | 10        | 9         | 9         |
| Winter |      | -3        | -1        | -2        | -3        | 0         | -2        |

Table 2. Temperature amplitude in Warsaw neighbourhood in the years 2010-14 [15].

| Season | Year | 2010 [°C] | 2011 [°C] | 2012 [°C] | 2013 [°C] | 2014 [°C] | Mean [°C] | Amplitude [°C] |
|--------|------|-----------|-----------|-----------|-----------|-----------|-----------|----------------|
| Spring |      | -6        | -7        | -3        | -11       | 0         | -5        | 15             |
|        |      | 22        | 26        | 28        | 25        | 25        | 25        |                |
|        | Summer | 10        | 10        | 9         | 10.5      | 9         | 10        | 11             |
|        |      | 32        | 30        | 33        | 33.5      | 30        | 32        |                |
| Fall   |      | -3        | -3        | -1        | -1        | -2        | -2        | 12             |
|        |      | 20        | 23        | 23        | 21        | 24        | 22        |                |
| Winter |      | -20       | -16       | -20       | -13       | -13       | -16       | 12             |
|        |      | 8         | 8         | 8         | 7         | 9         | 8         |                |

Figure 1. Variation of total irradiation in Warsaw neighbourhood during a day.

Total solar irradiation, see Figure 1, was approximated using the Gaussian function, i.e. assuming the normal distribution. Then the OriginPro 8 software was applied to generate the following expressions for summer and winter season, respectively:

\[
q_s(t) = \begin{cases} 
443.5 \exp \left( -2 \left( \frac{t-12.44}{6.17} \right)^2 \right) & \text{for the summer season} \\
242.3 \exp \left( -2 \left( \frac{t-11.62}{2.58} \right)^2 \right) & \text{for the winter season}
\end{cases}
\]  \( (2) \)
2.2. Governing equations
Heat in the building envelope was assumed to be transferred by two modes: heat conduction in the concrete layer and heat conduction and thermal radiation in the insulation. All thermal and radiative properties were assumed constant in each layer. The solar radiation was absorbed on the external surface of the building envelope treated as the blackbody. Grey body model was assumed for thermal radiation in the insulation layer, in which small spherical particles with the encapsulated PCM were distributed. The effect the microcapsules polymer shells is neglected. The PCM present in the particles undergoes the solid-liquid phase transformation in the range between the solidus and liquidus temperatures. The external and internal surfaces of the building envelope exchanged heat with the ambient air by convection. The one-dimensional heat transfer was assumed due to large transverse dimensions of the building envelope in comparison to its thickness. Moreover, the thermal equilibrium, i.e., equality of temperatures of the thermal insulation and encapsulated PCM particles was declared.

Then the energy equation took the following form, when the enthalpy formulation was used:

$$\frac{\partial (\rho_{ef} h_{ef})}{\partial t} = \lambda_{ef} \frac{\partial^2 T}{\partial x^2} + \sigma_{a,ef} \left( \int_{\Omega} i d\Omega - 4\sigma_b T^4 \right)$$

where: \((\rho_{ef} h_{ef})\) is the effective volumetric enthalpy, \(\lambda_{ef}\) – the effective thermal conductivity and \(\sigma_{a,ef}\) stands for the effective linear absorption coefficient of the PCM enriched insulation. The second term on the right hand side of the equation above is associated with a heat source following from difference between radiation energy absorbed and emitted by the thermal insulation. The symbol \(i\) denotes total radiation intensity, which is integrated over the spherical angle \(\Omega\) while \(\sigma_b\) is the blackbody constant.

The effective volumetric enthalpy is related to the volume fractions of the insulation \(\nu_i\) and PCM containing particles \(\nu_p\), their densities \(\rho_i\) and \(\rho_p\) as well as their specific enthalpies \(h_i\) and \(h_p\):

$$\rho_{ef} h_{ef} = \nu_i \rho_i h_i + \nu_p \rho_p h_p$$

The specific enthalpies can be determined from the formulae where the second one accounts not only for temperature but also the phase change present in the PCM:

$$h_i = c_i T$$

$$h_p = \begin{cases} 
    c_{ps} T & \text{for } T < T_{sol} \\
    (1 - \nu_{pl}) c_{ps} T + \nu_{pl} (c_{ps} T_{sol} + L) & \text{for } T_{sol} \leq T < T_{liq} \\
    c_{ps} T_{sol} + L + c_{pl} (T - T_{liq}) & \text{for } T > T_{liq}
\end{cases}$$

where: \(c_{ps}\) and \(c_{pl}\) are the specific heats of the solid and liquid PCM, \(L\) is the latent heat of PCM melting while \(T_{sol}\) and \(T_{liq}\) denote the solidus and liquidus temperature, respectively. The symbol \(\nu_{pl}\) is the volume fraction of liquid PCM in the microcapsules.

The liquid fraction varies with temperature and can be calculated from the expressions:

$$\nu_{pl} = \begin{cases} 
    0 & \text{for } T < T_{sol} \\
    \frac{T - T_{sol}}{T_{liq} - T_{sol}} & \text{for } T_{sol} \leq T < T_{liq} \\
    1 & \text{for } T > T_{liq}
\end{cases}$$
In the case of the aerated concrete the energy equation reduces to:

$$\rho_c c_c \frac{\partial T}{\partial t} = \lambda_c \frac{\partial^2 T}{\partial x^2}$$

(8)

where the symbols $\rho$, $c$ and $\lambda$ stand for the density, specific heat and thermal conductivity of the aerated concrete.

The radiation intensity was determined from the Radiative Transfer Equation [16, 17]:

$$\frac{di}{ds} = \frac{di}{dx} (e_\Omega \cdot e_s) = -\left(\sigma_{a,ef} + \sigma_{s,ef}\right) i + \sigma_{a,ef} \sigma_b T^4 + \frac{\sigma_{s,ef}}{4\pi} \int_{4\pi} i d\Omega$$

(9)

which presents variation of the intensity along the path $s$ in space (direction). The first term on the right hand side of the equation above is responsible for intensity attenuation due to absorption and out-scattering, the second term contributes to intensity enhancement due to radiation emission while the last term due to radiation in-scattering from other directions. The scattering was assumed to be isotropic. The symbols $e_\Omega$ and $e_s$ denote the unit vectors associated with direction $\Omega$ and the coordinate axis $x$.

In the PCM enriched thermal insulation radiation absorption and scattering occurs on fibres of a diameter of a few $\mu$m and PCM particles with the diameters usually lying between 50 to 100 $\mu$m. The effective linear absorption and scattering coefficients were determined from the following expressions:

$$\sigma_{a,ef} = \sigma_{a,i} + \sigma_{a,p}$$

(10)

$$\sigma_{s,ef} = \sigma_{s,i} + \sigma_{s,p}$$

(11)

where the second subscript denotes the radiative property of the thermal insulation $i$ or PCM-containing microcapsules $p$, respectively. The radiative coefficients were taken from [18] while these for the PCM microcapsules were evaluated from the formulae valid for the optical limit [19]:

$$\sigma_{a,p} = \frac{3v_p}{2d_p} \varepsilon_p$$

(12)

$$\sigma_{s,p} = \frac{3v_p}{d_p} \left(1 - \frac{\varepsilon_p}{2}\right)$$

(13)

where: $d_p$ denotes the particle diameter and $\varepsilon_p$ emissivity of its surface.

The boundary condition at the internal $A_i$ and external $A_e$ surfaces of the building envelope assumed the following form:

$$\lambda_i \left. \frac{\partial T}{\partial x} \right|_{A_i} = \alpha_i (T - T_i)$$

(14)

$$-\lambda_e \left. \frac{\partial T}{\partial x} + q_{rad} \right|_{A_e} = \alpha_e (T_e - T) + q_e (t)$$

(15)

where the radiative heat flux was determined from the expression:

$$q_{rad} = \int_{4\pi} i (e_\Omega \cdot e_s) d\Omega$$

(16)
It was also assumed that temperature distribution is continuous across the aerated concrete – thermal insulation interface and that this interface corresponds to the black surface completely absorbing thermal radiation.

### Table 3. Material properties of building materials [20].

| Property/Material          | Aerated concrete | Mineral wool |
|----------------------------|------------------|--------------|
| Density [kgm\(^{-3}\)]     | 800              | 130          |
| Specific heat [Jkg\(^{-1}\)K\(^{-1}\)] | 840              | 750          |
| Thermal conductivity [Wm\(^{-1}\)K\(^{-1}\)] | 0.38             | 0.042        |

### 2.3. Numerical solution and material properties

Numerical simulations were performed using ANSYS Fluent code. The problem was assumed to be quasi-2D with surfaces perpendicular to the y-axis treated as adiabatic. The regular mesh was generated using the quadratic elements (QUAD), the mesh quality was checked and the accuracy of calculations was verified by increasing the mesh density. The time step was assumed to be 60 s while the convective heat transfer coefficients at the internal and external surface of the envelope were specified to be \( \alpha_i = 7.69 \, \text{Wm}^{-2}\text{K}^{-1} \) and \( \alpha_e = 9.09 \, \text{Wm}^{-2}\text{K}^{-1} \), respectively [20]. The Radiative Transfer Equation was solved using Finite Volume Method [16, 17] with the spherical angle discretization corresponding to \( N_\theta N_\phi = 4 \times 8 \). The absorption and scattering coefficients of the thermal insulation had the values \( \sigma_a, i = 200 \, \text{m}^{-1} \) and \( \sigma_s, i = 800 \, \text{m}^{-1} \) [18, 19]. The regular emissivity of the microcapsules was assumed to be 0.7.

### Table 4. Thermo-physical properties of selected PCMs [21].

| Property/Material          | Paraffin C18 | Paraffin RT18_HC |
|----------------------------|--------------|------------------|
| Type                       | Organic      | Organic          |
| Participation mass in insulation [%] | 10            | 10               |
| Diameter of the microcapsules [µm] | 5             | 5                |
| Emissivity of the microcapsules | 0.7          | 0.7              |
| Solid phase temperature [K]  | 300          | 290              |
| Liquid phase temperature [K] | 301          | 291              |
| Latent heat [kJkg\(^{-1}\)K\(^{-1}\)] | 243          | 250             |
| Specific heat [kJkg\(^{-1}\)K\(^{-1}\)] | 2             | 2                |
| Thermal conductivity [Wm\(^{-1}\)K\(^{-1}\)] | 0.15          | 0.2              |

Initial condition for the simulations was obtain from the steady state solution of the considered problem by fixing the constant external temperature to its mean value for each season. When the model has reached the steady state, the external constant temperature was replaced by the temperature variable in time using the sol-air temperature [14]:

\[
T_e = T_e(t) + \frac{q_e(t)}{\alpha_e}
\]  

(17)

The system attained the fully periodic state after three days of the real time. Temperature and heat flux at each point of the mesh were recorded every 15 minutes of the real time.

Properties of the aerated concrete and mineral wool used are presented in table 3.
Phase change material was selected according to the following methodology. Distributions of the maximum and minimum temperature in the thermal insulation were found for no PCM present in the thermal insulation. The observed difference in temperature distributions between the summer and winter seasons excluded using a single PCM. Therefore a mixture of two different phase change materials was applied assuming that only part of the PCM will work in each season (summer/winter) in accordance to the material characteristic. Properties of the selected phase change materials are shown in table 4. For simplicity the specific heat and thermal conductivity of the solid and liquid phases were assumed equal.

![Figure 2](image1.png)  
**Figure 2.** Variation of heat loss from the room during a winter day.  
![Figure 3](image2.png)  
**Figure 3.** Distribution of the maximum temperature in the thermal insulation for absence and presence of solar irradiation.

3. Results and discussion
In order to investigate the effect of different modes of heat transfer and presence of the PCM in the thermal insulation on the distribution of the temperature, fraction of PCM that undergoes phase change and heat flow, a series of different simulations were carried out:

- Only heat conduction in the insulation layer and the variable ambient temperature,
- Heat conduction and thermal radiation in the insulation layer and the variable ambient temperature,
- Heat conduction and thermal radiation in the insulation layer and the variable ambient temperature and solar heat flux,
- Heat conduction and thermal radiation in the insulation layer and the variable ambient temperature and solar heat flux, presence of PCM microcapsules across the whole insulation layer,
- Heat conduction and thermal radiation in the insulation layer and the variable ambient temperature and solar heat flux, presence of PCM microcapsules only in the 3 cm outer layer of thermal insulation,
- Heat conduction and thermal radiation in the insulation layer and the variable ambient temperature and solar heat flux, presence of PCM microcapsules across the whole insulation layer with variable emissivity of the microcapsule surface.

At first the influence of radiation on the building envelope behaviour is considered. Figure 2 shows heat lost from the room in the winter season for the cases when thermal radiation is absent or present in the insulation. The significant increase in the heat loss is observed when the thermal radiation is accounted for. Distribution of the maximum temperature across the thermal insulation layer in the summer season, Figure 3, demonstrates the role of solar irradiation incident on the external surface of
the building envelope. The noteworthy difference in temperatures observed was important for selection of the appropriate PCM. In addition the greater difference between the minimum and maximum temperature (about 6°C) were found when the solar irradiation was included in the simulation.

**Figure 4.** Variation of temperature with time at the concrete-thermal insulation interface for a day in the summer season.

**Figure 5.** Variation of heat flux with time at the concrete-thermal insulation interface for a day in the summer season.

**Figure 6.** Variation of temperature with time at the concrete-thermal insulation interface for a day in the winter season.

**Figure 7.** Variation of heat flux with time at the concrete-thermal insulation interface for a day in the winter season.

The next four figures illustrate how presence of the PCM microcapsules and its distribution in the thermal insulation affects temperature and heat flux at the interface between the aerated concrete and insulation layers during a day in the summer season (Figures 4 and 5) and in the winter season (Figures 6 and 7). The figures present two cases of the PCM distribution: PCM uniformly distributed across the whole layer, PCM uniformly distributed only in the outer 3 cm layer of insulation. They are compared with the case where no PCM occurs in the thermal insulation. Presence of the PCM in the thermal insulation leads to a decrease in temperature fluctuations and heat flux. The extremum temperatures are shifted more to longer times the more part of the insulation layer been enriched in the PCM. The positive values of the heat flux correspond to heat flow from the concrete layer while the negative values into the concrete layer. The decrease in temperature and heat flux values is more visible for the summer than for the winter season.
Finally, influence of the emissivity of micro-capsules containing PCM was examined. The emissivity of the microcapsules surface was decreased from $\varepsilon_p = 0.7$ to $\varepsilon_p = 0.5$ and $\varepsilon_p = 0.3$ respectively. Figures 8 and 9 show, that the decrease in emissivity causes small decrease in temperature fluctuations when the PCM is spread over the whole insulation layer. The decrease is greater for the summer season. The heat flux fluctuations on the room side of the building envelope are decreased by about 8% if the emissivity of the microcapsule surface is reduced to $\varepsilon_p = 0.3$. Furthermore, if the PCM only appears in the outer layer of the insulation, changes in temperature distribution and heat flux are almost unnoticeable.

4. Conclusions
Temperature distribution in the two-layer building envelope and heat flux leaving it depend on thickness and thermal and radiative properties of the layers, ambient atmospheric condition, volume fraction, diameter and emissivity of the microcapsules containing PCM. Comparison of different cases of heat flow through the envelope was carried out. These cases included presence or absence of PCM and thermal radiation in the insulation, effect of emissivity of the PCM microcapsules as well as an effect of solar radiation or its lack on the ambient side of the envelope. Two ways of the PCM distribution in thermal insulation in the insulation were also considered.

The choice of the appropriate PCM or its mixture as in the studied case should be performed using the predicted minimum and maximum temperature in the insulation accounting for different variation of the ambient temperature and solar irradiation in the summer and winter seasons of a year. The results of calculation show that radiative heat transfer in the light-weight thermal insulation plays an important role in heat transfer and that presence of the PCM in the thermal insulation contributes to the significant reduction in temperature and heat flux fluctuations in the building envelope. Therefore influence of radiative properties of the PCM-filled microcapsules should be further studied including different microcapsule diameter and the wavelength dependence of their radiative properties. Due to relatively long duration of the PCM melting/freezing process, poor heat transfer between the microcapsules and the surrounding gas present in the insulation as well as the long-distance interaction of thermal radiation the microcapsules may not be in thermal equilibrium with the surrounding insulation therefore two temperature model of heat transfer through the PCM enriched insulation should be considered in the future.
References
[1] Tyagi V V and Buddhi D 2007 Renew. Sust. Energ. Rev. 11 1146
[2] Soares N, Costa J J, Gaspar A R and Santos P 2013 Energ. Buildings 59 82
[3] Torres Ledesma J, Łapka P, Domański R and Casares F S 2013 Therm. Sci. 17 431
[4] Jaworski M 2014 Appl. Therm. Eng. 35 212
[5] Cabeza L F, Castell A, Barrenche C, Garcia A and Fernandez A I 2011 Renew. Sust. Energ. Rev. 15 1675
[6] Kissock K and Limas S 2006 ASHRAE Trans. 112 509
[7] Ahmad M, Bontemps A, Sallee H and Quenard D 2006 Energ. Buildings 38 673
[8] Jaworski M, Łapka P and Furmański P 2014 Appl. Energ. 113 548
[9] Kosny J, Yarbrough D W, Petrie T and Mohiuddin S A 2008 Performance of thermal insulation containing microencapsulated phase change material Thermal Conductivity 29: Thermal Expansion 17 ed J R Koenig and H Ban (Birmingham: DEStech Publications, Inc.) pp. 109–119
[10] Kosny J, Kossecka E, Brzezinski A, Tleoubaev A and Yarbrough D 2013 Numerical and experimental thermal analysis of PCM-enhanced insulations Thermal Conductivity 31: Thermal Expansion 19 ed L I Kiss and L St-Georges (Lancaster: DEStech Publications, Inc.) pp. 157–167
[11] Heim D and Clarke J A 2004 Energ. Buildings 36 795
[12] Zhu N, Ma Z and Wang S 2009 Energy. Convers. Manage. 50 3169
[13] Zhang M, Medina M A and King J 2005 Int. J. Energ. Res. 29 795
[14] Kossecka E and Kosny J 2010 Budownictwo i Inżynieria Środowiska 57 309
[15] http://www.imagw.pl/klimat/
[16] Łapka P and Furmański P 2010 J. Heat Transfer 132 023504
[17] Łapka P and Furmański P 2012 Int. J. Heat Mass Transfer 55 4941
[18] Boulet P, Jeandel G, Morlot G, Le Bail A and Bardon J P 1994 Radiative transfer in fibrous insulators. Application to carbon and silica fibres Thermal Conductivity 22 ed T W Tong (Lancaster: Technomic Publishing Company, Inc.) pp.760–770
[19] Saboonchi A, Sutton W H and Love T J 1988 J. Thermophys. Heat Tr. 2 97
[20] PN-EN ISO 6946 2008 Thermal resistance and heat transfer coefficient (in Polish)
[21] http://www.rubitherm.de/