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Experimental Investigation and Mathematical Modelling of Thermal Performance Characteristics of Textiles Incorporating Phase Change Materials (PCMs)

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Abstract. Impregnation of textiles (fabrics) by phase change materials (PCMs) changes their thermal properties. High thermal capacity of PCMs, due to large enthalpy of phase change (latent heat), increases the potential of these materials for heat accumulation, but also modifies heat transfer in transient states what improves their insulating characteristics. The paper presents selected results of both experimental and theoretical investigation of the thermal behavior of textiles impregnated with phase change materials, PCMs, under variable thermal loads. Thermal capacity of textiles containing different amounts of microencapsulated PCM were measured with DSC. Then, their thermal behavior characteristics were investigated under irradiation from a solar simulator (heating phase) and during cooling in the regime of natural convection. Mathematical model of heat transfer in the textiles, including radiative and convective boundary conditions, was formulated. Computer simulations of the processes under study, validated on the base of experimental results, allowed to determine important properties of the textiles, such as coefficients of absorption and transmission for solar radiation. Overall thermal characteristics of the textiles, i.e. temperature variations under different thermal loads, are also presented in the paper.

Keywords: Phase Change Materials PCM, Functional Textiles, Thermal Energy Storage, Thermal Performance Characteristics.

Conference topic: Energy for Buildings.

Introduction

In thermal engineering the term Phase Change Materials (PCMs) refers to materials that undergo phase thransition during operation of the system or device in which they are used. Phase transition, usually melting-solidification, is associated with the change of enthalpy (latent heat, since the proces is theoretically isothermal), and these materials are selected so that this property is as high as possible. This is because the ability to accumulate a large amount of heat with a small temperature change is the most important feature of PCMs. Nowadays, the range of applications of PCMs include nearly all fields of engineering activities. First of all they are used for thermal energy storage, just for their high thermal capacity. In this area a variety of techniques are known and developed, starting from simple heat storage units in a form of heat regenerators, to sophisticated methods based on the incorporation of PCMs, e.g. in buildings envelopes (Jaworski 2014; Rusowicz *et al.* 2014; Soares *et al.* 2013; Zalba *et al.* 2003). Thermal inertia of PCMs is utilisaed for temperature stabilisation, e.g. of electronic devices (Jaworski 2012), medical and food products durng their storage and transportation as well as in pharmaceutical and chemical industry (Bühler *et al.* 2013).

Modification of the fabrics (textiles) by addition of phase change materials is dynamically developed technology (Mondal 2008; Sarier, Onder 2012). PCM content increases thermal capacity of the textile, which in turn improves also its thermal resistance properties, especially in transient conditions.

PCM impregnated textiles, as functional materials, currently find numerous applications. Their development started with the use in space suits and gloves to protect astronauts from the bitter cold when working in space. Contemporary applications include sportswear, such as snowboard gloves, shoes, underwear and active wear for ice climbing, cycling and running; bedding and related accessories; automotive seat cover textiles; motor cycle helmets. Medical applications belong to those of a great importance, these include surgical apparels, patient bedding materials, bandages and products used to regulate patients temperature in intensive care units. Similarly, textiles are used for protective clothes for firefighters, metallurgists etc. (Bühler *et al.* 2013; Mondal 2008; Safavi *et.al.* 2015; Sarier, Onder 2012; Ying *et al.* 2004). Textiles containing PCMs are considered to be used in buildings as heat storage elements in the form of window blinds, wallpapers etc., to accumulate heat or cold, thus improving thermal comfort inside the room.

Technologies of PCM impregnated fabrics' manufacturing undergo continuous development. The most commonly used are: fiber technology, coating and lamination. In the first one PCM is added to a polymer solution prior to fiber extrusion, i.e. PCM is contained in fibres. In two other technologies the fabrics are complimented with PCM –

either in the form of a paste containing a PCM and other substances (binders, surfactants etc.) wich are necessary to obtain stable structure, or in the form of polymer film which is applied to the surface of the fabric (Nejman, Goetzendorf-Grabowska 2013; Cieślak *et al.* 2015).

New technologies of the manufacturing of PCM impregnated textiles imply the necessity of the investigation of thermal and physical properties of these structures, as well as the study of the thermal characteristics of the final products under conditions of thermal loads similar to those in which they will be used. The paper presents the results of experimental investigations of the fabrics containing microencapsulated PCM. Also, mathematical models of heat transfer through the fabrics subjected to solar radiation were developed. Computer simulations in conjunction with experimental study allowed the identification of crucial parameters of the fabrics which are responsible for their thermal behaviour in transient conditions.

Materials and methods

The objects of the research were polyester column knitted fabrics modified with microencapsulated PCM of the following composition: 85–90 wt.% of paraffins and 10–15 wt.% of polymer shell. Two types of commercial MPCM from Microtek Laboratories, USA, containing the following paraffin: n-hexadecane (in this work it is depicted as 18, due to the level of melting point) and n-eicosane (depicted as 37) were tested. The knitwear fabrics were coated with a polymer paste containing 40% of MPCM and binders (Nejman, Goetzendorf-Grabowska 2013). Samples of the fabrics coated on one side and on both sides, with different configurations of PCM were investigated. Thermal properties of the fabrics and samples with PCM coatings were measured using differential scanning calorimeter (DSC, Perkin-Elmer). Detailed characteristics of enthalpy vs. temperature for both heating and cooling were obtained. Figure 1 shows enthalpy vs. temperature curves for two samples of fabrics with PCM coatings. A clear hysteresis of these characteristics is visible.

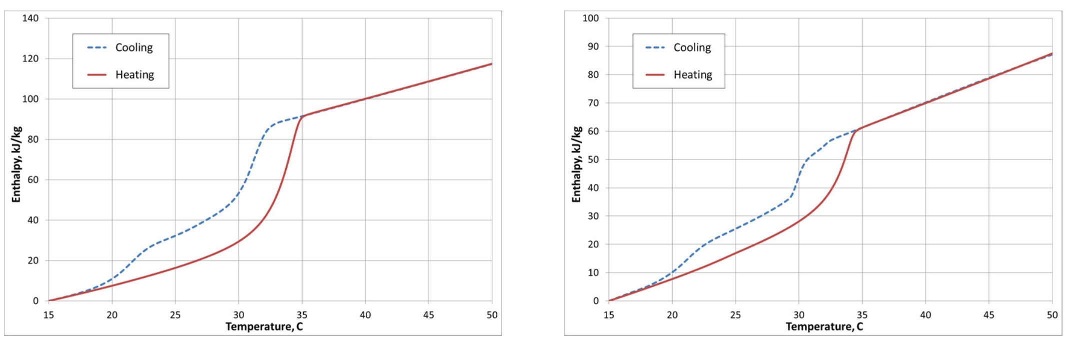


Fig. 1. Enthalpy vs. temperature characteristics measured during heating and cooling of two fabrics covered with PCMs: 37-type on both sides (on left) and different PCMs on both sides 37/18 (on right)

Currently there are no generally accepted standards for testing thermal characteristics of systems accumulated heat on the basis of PCM, this also applies to fabrics impregnated with these substances (Mondal 2008). Therefore, the test methods and procedures are tailored to specific cases. The main aim of this experimental research was to determine the temporal temperature variations of the fabrics under study subjected to specific thermal loads. Heating process was due to radiation, while cooling phase was performed in natural convective regime to the surrounding air. Different ways of positioning of the fabrics were also taken into account: a fabric suspended freely in the open space, a fabric as in the previous case but behind the glass (window) and a fabric mounted on the OSB board (building material). All this configurations were the models of specific buildings applications of PCM impregnated fabrics, i.e. as window blinds and wallpapers.

Tests were carried out under the simulator of solar radiation. Solar simulator used in the lab generates the radiation spectral characteristics which is in accordance with AIR MASS 2 spectral distribution according to the standard ASHRAE 93-77 (Wnuk 2008). It meets the requirements of this standard relating to: the spectral characteristics, the uniformity of irradiation flux density of radiation, collimation and regime of the operation. Radiation intensity was measured in the plane of the fabric (at the level of the location of temperature sensors) using a pyranometer (Kipp & Zonen). Temperatures at different locations of the fabrics were measured by means of K-type thermocouples (Omega, USA) glued to the surface. Temperatures were recorded using an ADDA converter (National Instrument, PCI-6281 with module SCB-68). Figure 2 shows a test-fabric mounted on the experimental set-up (a case with a fabric behind the glass pane).

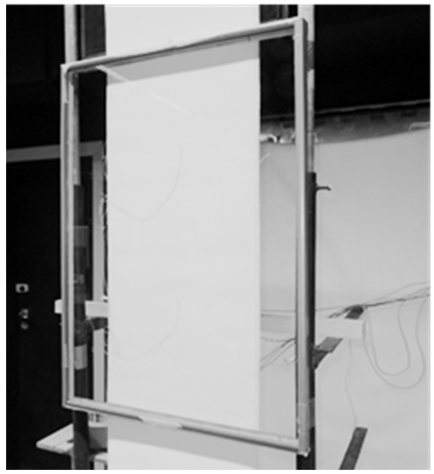


Fig. 2. A sample textile located behind the glass pane at the experimental set-up

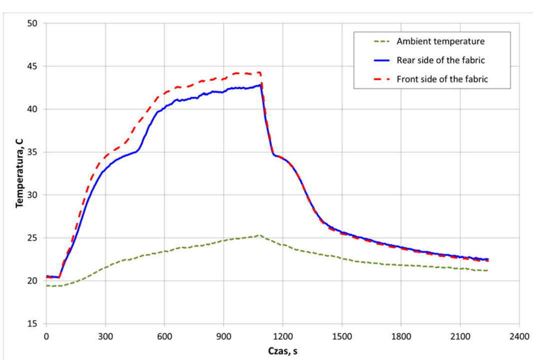
Results of the experimental study

A number of measurements for different fabrics and different configurations were performed. In each case, the test consisted of two phases, during which indications of temperature sensors were recorded:

- radiation heating (with the use of solar simulator) until a steady state or significant overheating (above melting point of PCM) was achieved. In this phase intensity of radiation was controlled and recorded. The level of intensity of radiation was selected during preliminary tests, so as to be able to melt PCM (about 700 W/m^2).
- cooling the fabric in natural convection conditions after turning off the solar simulator; this phase lasted until fabric's temperature reached the level close to the ambient temperature.

In the paper selected results are presented and discussed. Fabrics coated on both sides with the layers containing PCM have the highest (among the analysed) thermal capacity and therefore their thermal characteristics are most pronounced. This is why results of their investigation were selected for this paper.

Figure(s) 3 show the result of the test for 37/37 fabric freely hanging in an open space. Surface temperatures are the average of the indications of two thermocouples mounted on each side. Figure on right shows the temporal variations of intensity of radiation. In this case (freely hanging fabrics), as compared to the others, the environmental impact is not so intense – radiation from the simulator is not disturbed by the glass, and there is no transport and accumulation of heat in the OSB board, the cooling is due to natural convection conditions in the open air.



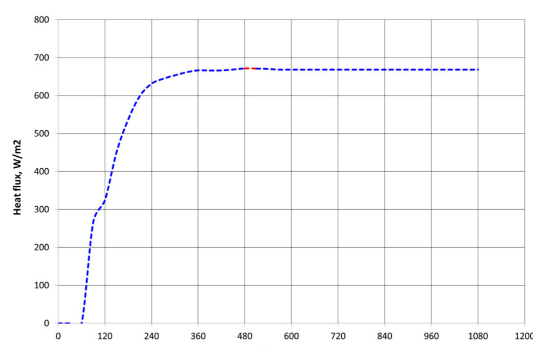


Fig. 3. Temperature variations of the surface of the 37/37 fabrics (left) and intensity of radiation during heating phase (right)

A fabric impregnated with PCM can be treated as a heat storage unit/module. The temperature curves shown in Figure 3 are typical for the processes of charging and discharging of heat storage unit based on PCM. High intensity of radiation with a low heat capacity is the reason for very high rate of temperature rise of the fabric. However, the melting phase is clearly visible; it is manifested by inhibition of the rate of heating. After completion of the phase transition a temperature relatively quickly reaches a steady state – radiation energy absorbed in the fabric is balanced by both convective heat flux and radiation to the environment (the range of the process during which the temperature curve of the fabric is nearly parallel to the ambient temperature curve). The fact that heat fluxes to the environment (convective and radiative) are large relative to the accumulation capacity of a fabric provides high cooling rate after switching off the simulator. This rate decreases after reaching the solidification temperature of the PCM, followed by a short phase transition period (lasting approx. 100 s). After PCM solidifies fabric's temperature slowly tends to the ambient temperature.

Figure 4 shows the change in the surface temperature of fabric attached (adhered) to the OSB board – this configuration can be regarded as a model of wallpaper. The measurement was carried out with similar characteristics of the radiation intensity as in the previous case (Fig. 3). In comparison to the previous case, one can see two distinct differences, i.e. an extension of the duration of both phase transformations during heating and cooling, which is due to the fact that part of the radiation energy is absorbed by the OSB board, which has a relatively large heat capacity in relation to the fabric itself. The second difference is the lack of steady state in a range of temperatures obtained during the test. In the previous test a steady state was achieved at a level of 43–44 °C, in this case the temperature grew even after exceeding the level 46–47 °C. This behavior follows from the fact that one side of the fabric is obscured by the board and heat losses due to convection and radiation are much smaller. These heat fluxes determine the level of steady state, cooling rate balancing the radiation from solar simulator requires much higher fabric's surface temperature.

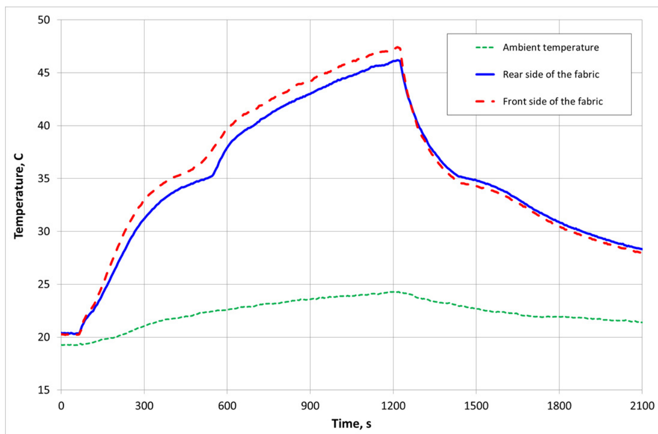


Fig. 4. Temperature variations of the surface of the 37/37 fabrics on OSB board

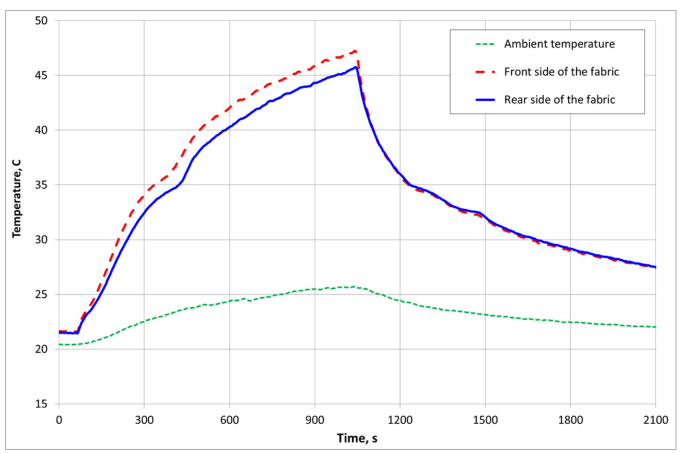


Fig. 5. Temperature variations of the surface of the 37/18 fabrics on OSB board

Figure 5, for comparison, shows the thermal characteristics (recorded in the same conditions of thermal loads) of the fabric coated on both sides by PCM of different melting temperatures, i.e. a fabric of type 37/18. One PCM undergoes a phase transition in the temperature range approx. 35 °C, the second one at a lower temperature, approx. 18 °C. This fabric has different characteristics of thermal capacity; the overall enthalpy of phase transition is distributed over wider range of temperature. During the tests, since heating started from the temperature level above melting point of PCM-18, not the whole thermal capacity of this composite (PCM37/18) was utilized. Therefore, the rate of change of temperature is greater, and the times of phase transitions shorter.

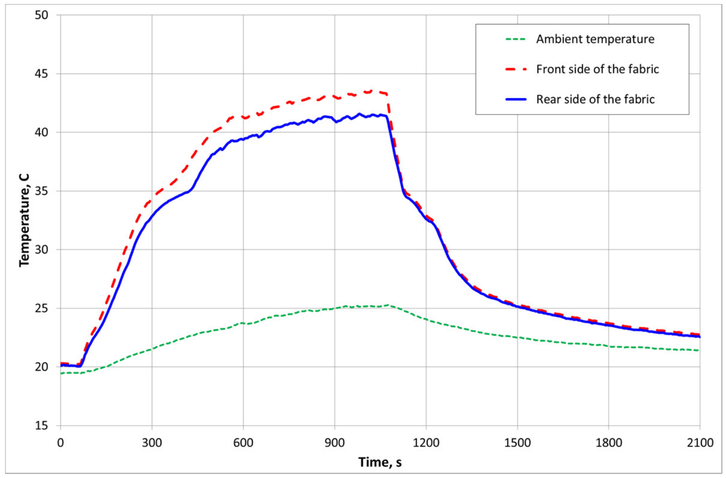


Fig. 6. Variations of the temperature of the sample during an experimental test with a freely hanging textile of type 37/18

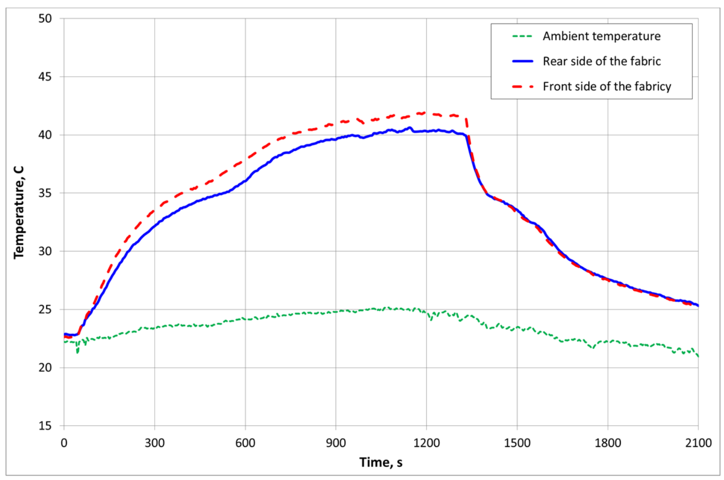


Fig. 7. Variations of the temperature of the sample during an experimental test with a the textile of type 37/18 behind the glass pane

Figures 6 and 7 show the results of measurements of the fabric 37/18 for two cases: hanging freely and located behind the window relative to the radiation source (the latter case is a model of a window blind for solar radiation heat accumulation). Since the energy flux coming from the simulator is damped by the glass, the rate of change of temperature during heating is reduced (Fig. 7). Also the temperature of steady state (equilibrium between cooling rate and absorbed radiation flux) is much lower.

Mathematical model and results of computer simulations

The aim of this part of the research was to develop a mathematical model of heat transfer in PCM impregnated fabrics subjected to environmental impacts by radiation and convection. Due to the small thickness of the fabrics (about 0.52 mm for the fabric covered on both sides by PCM), as compared to other dimensions, the problem can be treated as one-dimensional, and even lumped parameter approach can be used. Figure 8 shows physical models of the problem for which mathematical models were formulated.

In case of 1D approach spatial and temporal, $T(x,\tau)$, temperature distribution in the fabric is described by heat conduction equation in the form

$$\rho c_p\left(\frac{\partial T}{\partial \tau}\right)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) \tag{1}$$

which is supplemented with initial condition

$$T(x,0)=T_0 \tag{2}$$

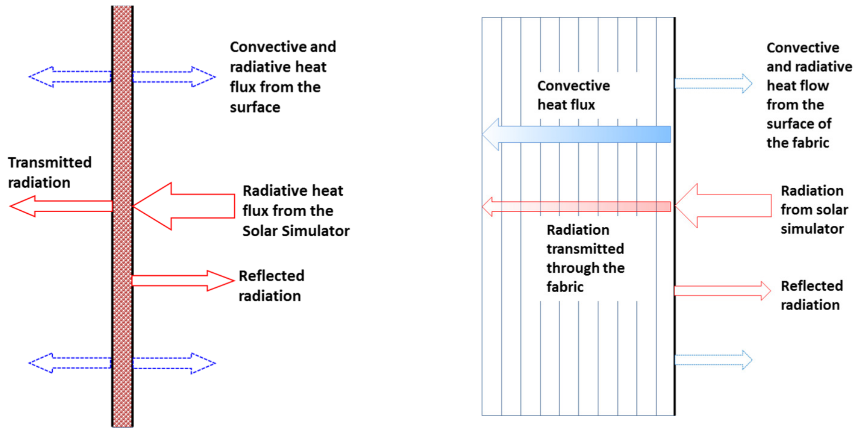


Fig. 8. Zero-dimensional, i.e. lumped thermal capacitance approach (left) and one-dimensional (right) models of heat transfer through a fabric layer

and boundary condition

$$q_s = a\,q_{sol} - \alpha\left(T_s - T_a\right) - \varepsilon\,\sigma\left(T_s^4 - T_{sur}^4\right) \tag{3}$$

where: ρ – density, c_p – specific heat, λ – thermal conductivity, a – absorptivity of the surface, α – heat transfer coefficient, ε – emissivity, T_s – surface temperature, T_a – air temperature, T_0 – initial temperature, T_{sur} – temperature in the vicinity of the system, for radiation heat transfer, q_{sol} – heat flux from the solar simulator.

Convective heat transfer to the ambient air is due to natural convection. In the model simplified correlation by McAdams was chose (Bergman *et al*. 2011). Base on this correlation heat transfer coefficient is described by the formula

$$\alpha = \frac{\mathrm{Nu}\,\lambda_a}{L} = 0{,}1\cdot\left(\frac{g\,\beta\,\Delta T}{\nu^2}\,\mathrm{Pr}\right)^{1/3}\frac{1}{\lambda_a}\,, \tag{4}$$

where: L – height of the sample, β – thermal expansion coefficient, Pr – Prandtl number, ν – kinematic viscosity, index a refers to the air.

Since the problem with phase transformation of one of the components is under study, it is more convenient to use an integral form of heat conduction

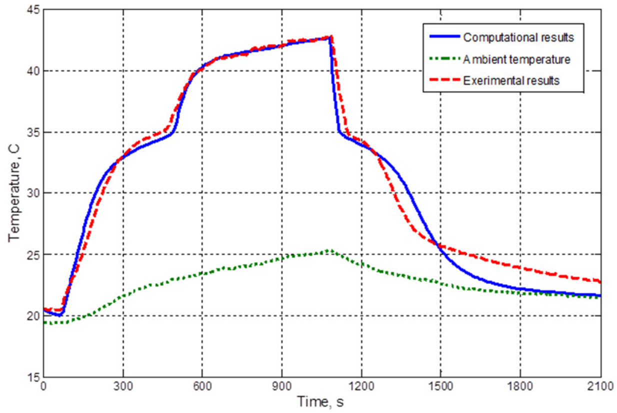
$$\int_V \rho\left(\frac{\partial h}{\partial \tau}\right)\mathrm{d}V = -\int_S q_{tot}\,n\,\mathrm{d}S\,, \tag{5}$$

where: h – specific enthalpy, V – volume, S – boundary of the system, q_{tot} – total heat flux at the boundary. In this approach any relation between enthalpy and temperature can be taken into account, also when hysteresis occurs. In our study the real $h(T)$ characteristics – such as those shown in Figure 1 – were used.

The models of heat transfer in the fabrics were solved numerically, using control volume approach (1D model) with Euler scheme for integration in time. Selected results are shown in this paper.

Temperature variations of the fabric over time under variable thermal loads depend on many factors, such as intensity of radiation, absorption coefficient, ambient temperature (which varies with time), convective heat transfer coefficient as well as average thermal properties of the substance (material of the fabric). Some of these factors are known (e.g. as the results of measurements), some of them can be estimated using adequate correlations (heat transfer coefficient). The others, however, must be predicted in the course of experimental validation of the model used in the study. That is, e.g. absorption coefficient for solar radiation.

The first example results refer to the heating and cooling of the fabric with both sides covered by PCM type 37 (i.e. PCM with melting point equal to 37 °C). Here, an experimental test with the sample freely hanging was simulated numerically. Results of the both calculated and measured temperatures of the sample are shown in Figure 9. In the figure on the right the temporal variations of radiative heat flux from solar simulator measured at the surface of the sample are shown. These characteristics of heat flux, as well as variable ambient air temperature (dotted line in the figure) were the input data for the computer simulation. Also enthalpy vs. temperature with hysteresis (Fig. 1, left) were taken into account. Cooling phase of the process was due to natural convection, with the same intensity from both sides. Here, experimental temperature is an average of indications of thermocouples connected to the rear surface. Indications of the sensors on the front surface, especially during heating, can be treated as overestimated, due to direct radiation on the thermocouples.



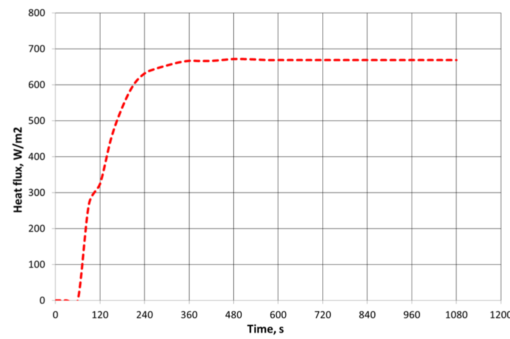


Fig. 9. Comparison of the results of computer simulation and experimental measurements of the PCM-textile (type 37/37) temperature variations; radiative heat flux measured during an experiment (in right)

The temperature profiles (computational results) shown in Figure 9 are the results of many numerical experiments (validation of the mathematical model), aimed at achieving good fit with experimental results. A relatively good correlation, particularly during heating phase, and during quasi-steady state (prior to excluding the solar simulator) was obtained for the following parameters:

– density of the fabrics related to the surface area, $\rho_s = 0.313$ kg/m^2;
– coefficient of absorption of radiations, $a = 0.245$;
– emissivity, $\varepsilon = 0.26$, (for both sides);
– heat transfer coefficient, $\alpha = 1.15 \cdot \Delta T^{1/3}$ (the same on both surfaces).

Low values of the coefficient of absorption of radiation and emissivity of the surface raised serious doubts, prompting to perform additional measurements at the experimental set-up. The purpose of these measurements is to estimate the radiation flux passing through the fabric and the reflected flux. For the fabric of the type 37/37, coefficient of transmissivity was measured to be about 0.23 (based on the measurement of radiation behind the sample with the use of pyranometer). Accurate measurement of reflectivity of surface of the fabric was not possible with the possessed devices (pyranometer screened the source of radiation), but the obtained results indicated that the up to 50% of radiation coming from the simulator can be reflected from the surface of the fabrics.

The second case refers to the thermal behaviour of the fabric, sides of which are covered by different PCMs, i.e. a fabric type 37/18. A comparison of computational results with corresponding experimental ones is presented in Figure 10. These results were obtained for the following input data:

– density of the fabrics related to the surface area, $\rho_s = 0.297$ kg/m^2;
– coefficient of absorption of radiations, $a = 0.22$;
– emissivity, $\varepsilon = 0.26$, (for both sides);
– heat transfer coefficient, $\alpha = 1.15 \cdot \Delta T^{1/3}$.

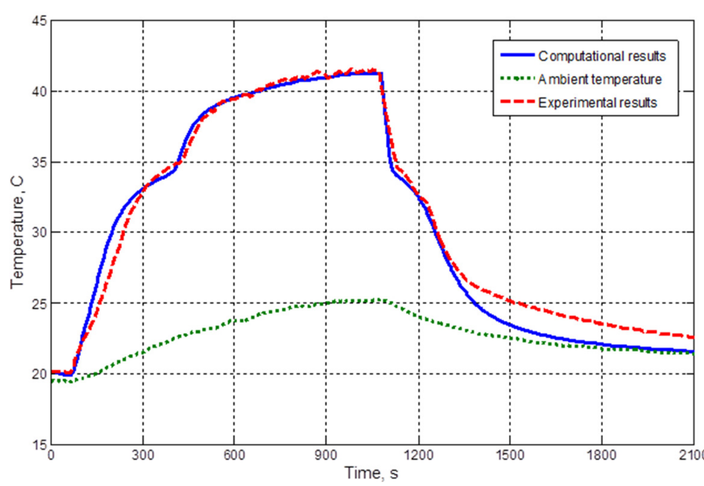


Fig. 10. Comparison of the results of computer simulation and experimental measurements of the PCM-textile temperature variations; textile covered by different PCMs (type 37/18)

Conclusions

The fabrics under study are characterized by a relatively low heat capacity, due to the small mass fraction of the coating containing PCMs. For double-sided fabrics of type 37 a mass fraction of the coating is approx. 45%. In other fabrics (especially with single side coatings) this ratio is much lower.

The characteristic of enthalpy vs. temperature (including hysteresis for heating and cooling phases) significantly influences the thermal characteristics of the fabrics under variable thermal loads. For some PCMs configurations (e.g. 37/18) cooling/solidification phase is extended in time. Also, full solidification of PCM requires considerable super-cooling in relation to equilibrium phase change temperature.

The small thermal capacity of the fabrics (in relation to the surface area) results in high rates of temperature change during radiative heating. This applies also to the time of phase transitions, i.e. time of melting of PCM is very short. Cooling of the fabrics in natural convection conditions also proceeded very quickly. Solidification of phase change material took approx. 100 s for the temperature difference (between melting point and ambient temperature) equal to approx. 12 °C.

The fabrics impregnated with phase change material, referred to as PCM-37, require a relatively high intensity of radiation in order to ensure melting of PCM. At ambient temperature in the range 20–25 °C, and for radiation intensity approx. 500 W/m^2, a steady state was reached at a temperature of the fabric close to melting point which is not enough for phase transition to proceed. For building applications (e.g. for the stabilization of room temperature by absorption of excess heat) PCMs of lower metling points should be used.

It was observed that the location of the fabrics close (or in direct contact) to the other surfaces has a very large impact on their thermal behavior. In case of OSB boards, this is due to their high thermal capacity (in relation to thermal capacity of the fabrics). In case of the fabrics located behind the glass pane the problem is more complex. Not only absorption of some part of radiation by the glass, but also heating of the air in the gap between the glass and the fabrics and complex air circulation in this gap influence an overall thermal characteristic of the fabric.

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Disclosure statement

Authors hereby declare that they do not have any competing financial, professional, or personal interests from other parties.

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