Determination of thermal properties and characteristics of PCM based heat storage elements for application in building envelope

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Abstract

This paper presents results of experimental investigation of thermal properties (heat capacity, thermal conductivity) of gypsum-PCM (phase change material) and concrete-PCM composites, and thermal characteristics of building elements made of these composites. Commercial, micro-encapsulated PCMs (Micronal, BASF), were used as energy storage substances. These PCMs were mixed with gypsum (used for internal facades) at different concentrations (up to ca. 37% weight). Thermal capacities were measured using differential scanning calorimeter (DSC). For selected compositions the samples of building elements were prepared (set of temperature sensors, thermo-couples, were imbedded in the samples) for the thermal characteristics investigations. In these experiments temporal temperature variations of the samples in unsteady conditions (radiation and temperature in the vicinity of the sample) were measured. Thermal behaviour of plasterboard containing PCM subjected to solar radiation (from solar simulator) and in natural convection cooling, with the reference to ordinary plasterboard, was also investigated.

1. Introduction

High thermal capacity of building structure contributes the enhance of thermal comfort of heavy constructions, reduction of energy consumption for heating/cooling, and also allows very efficient use of solar energy through its accumulation. In contemporary, in light weight buildings, substantial increase of thermal inertia can be achieved through integration of phase change materials (PCMs) into building elements, such as plaster boards, concrete blocks, ceiling panels etc.

Thermal characteristics of building construction materials containing PCM were investigated by many research groups in both natural and laboratory conditions. Schossig et al. [1] measured thermal characteristics of sample plaster board with PCM and also the influence of such plaster boards on thermal comfort in real office rooms. Plaster board containing from 20 to 40% of microencapsulated PCM reduced maximum temperature by up to 4 K. Similar investigations were performed by Cabeza et all. [2]. They compared the temperature variations in two cubicles, one of which was made of concrete, the other one of concrete containing PCM (Micronal, BASF). Dumping of temperature variation by a few degrees was recorded. Very important observation was the lack of the change of mechanical properties of concrete with PCM after approximately 6 months of operation. Structural insulated panels containing pipes filled with PCM were investigated in natural conditions in two houses – one as a reference, by Medina et al. [3]. For the PCM concentration 10 and 20% reduction of average daily heat transfer across the panel was between 32 and 38%. Carbonari [4] investigated wall panels containing PCM in the form of plastic rigid containers. Tests were performed in special room with solar simulator as a source of heat flux disturbances. The aim of these experiments was to get information for the validation of numerical code for simulation of 2-D heat transfer with phase change. Special, multilayer panels for ceiling structure consisted of concrete, PCM enclosed in stainless-steel container and rooftop layer, ware tested in special lab scale set-up, which allows the comparison to the traditional ceiling structure [5, 6]. The results of the temperature measurement across the slabs for different environmental condition and different thickness of PCM layer were also used in validation of numerical codes. Kuznik et all. [7, 8] used a full-scale test room with fully controlled environment, that allows the performance of differential tests, to measure thermal performance of multilayer walls samples with 5 mm PCM layer. Reductions of room temperature fluctuation due to PCM layer were observed. Voelker et al. [9], using two-room (differential) experimental set-up measured the influence of PCM-containing plaster boards on internal temperature. They analyzed plaster boards of different thickness and with different PCMs: microencapsulated paraffin and macro-encapsulated calcium chloride hexahydrate.

In this paper selected results of extensive experimental tests of thermal properties of gypsum-PCM mixtures and thermal performance of boards made of such composites are presented. Physical properties, such as thermal capacity and thermal conductivity, are necessary for mathematical modeling of heat transfer process in building elements with PCM, and thermal characteristics of these elements in transient conditions are used in validation of numerical codes that are being developed.

2. Thermal properties of gypsum-PCM composites

Differential scanning Calorimeter (DSC, Perkin Elmenr) was used to measure thermal capacity of composites of gypsum (produced by Knauf) with microencapsulated PCM – two types of Micronal (BASF) of melting point 23°C ((*Micronal* DS 5001X) and 26°C (*Micronal* DS 5008X) were used. For both types of Micronal six samples of PCM concentrations between 14 and 37% (by weight) were prepared. DSC tests were performed with scanning rates 2 and 5 K/min – example DSC curve is shown in Fig. 1.

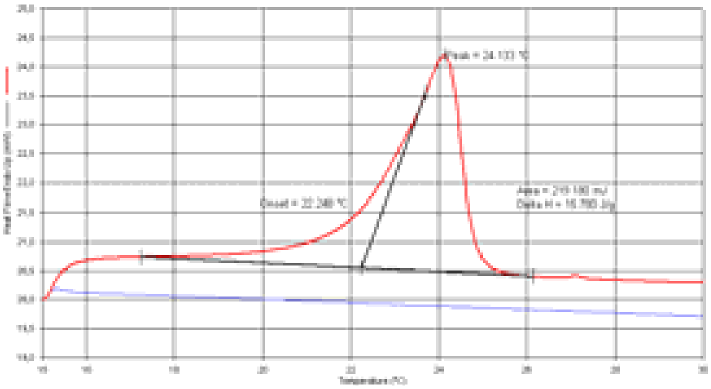

Fig. 1. DSC curve for composite of gypsum with 18,6% (w.) of *Micronal* DS 5008X (melting point 23,5°C).

Based on DSC diagrams enthalpy changes over selected temperature range (relevant for the building applications of composites under consideration) were determined for each gypsum-PCM composition. Enthalpy vs. temperature functions are used in the computer simulations of transient heat transfer processes in energy storage elements. For preliminary analysis of such elements, e.g. where their thermal capacity is required, effective specific heat data are sufficient. Fig. 2 shows values of this property for composites with both types of *Micronal*, and for different concentrations of PCM. Effective specific heat was determined for two temperature ranges – 10 K and 6 K. Because of different melting points for each *Micronal*, individual ranges were slightly shifted, in order to fully cover phase change process (both melting and solidification requires finite change of temperature, even if the process is very slow – such as in building applications – overheating or overcooling by a few degrees is necessary). Since latent heat of both PCMs is nearly the same (110 kJ/kg), a difference in effective specific heats is probably caused by the difference in phase change characteristics, i.e. enthalpy vs. temperature variations.

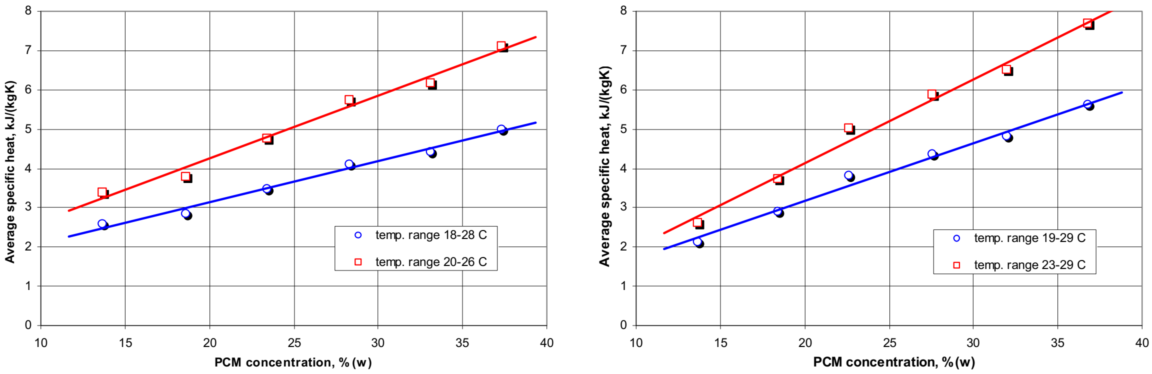

Fig. 2. Average (over given temperature range) specific heat of gypsum-PCM composites in function of PCM concentration; left – *Micronal* DS 5008X; right – *Micronal* DS 5001X.

3. Thermal characteristics of building elements containing PCM

3.1. Heating and cooling of plaster board with PCM in natural convection

Experimental investigations include also measurements of thermal conductivity of gypsum-PCM composites. The tests are performed at plate apparatus in steady states, and haven't been completed yet, because they are very time-consuming, especially when melting point is inside the temperature range. But one of the samples for thermal conductivity measurements was used in the evaluation of thermal behaviour of the composite in transient thermal conditions.

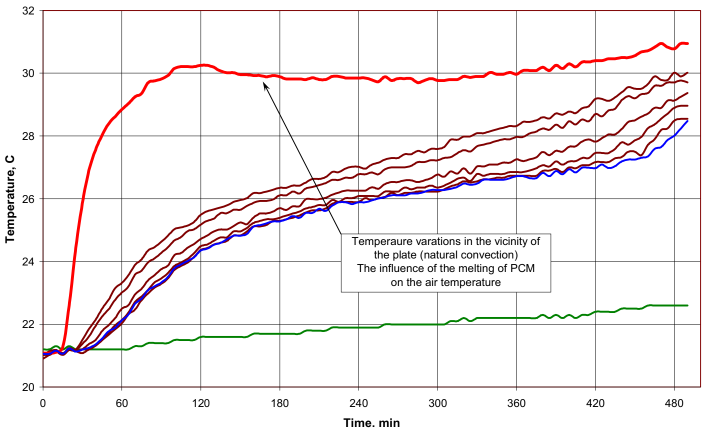

Fig. 3. Temperature variations in the sample during heating.

In the plate of dimensions 250×250×34 mm, made of gypsum with 18,4% of Micronal (DS 5001X), seven thermocouples have been embedded (two on the surfaces and five inside). Two tests were performed – for heating and for cooling by the air in natural conditions. Initially sample was heated to uniform temperature (in plate apparatus), and then it was exposed to environment of controlled temperature. For heating initial temperature equals to 21°C, and environment temperature equals to 32°C, for cooling temperatures were reversed. Figure 3 shows the temporal variation of temperature of the sample's surfaces and inside the sample during heating by the air of 32°C. Red line depicts the upper surface temperature and it the influence of PCM's melting on this temperature is clearly visible. Similar effects have been observed during cooling of the sample (Fig. 4) – green line shows the temperature very close to the lower surface of the sample, and its decline has been stopped by the solidification of the PCM.

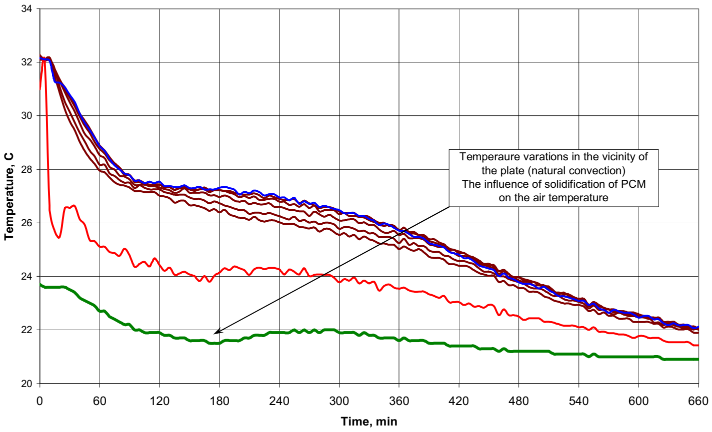

Fig. 4. Temperature variations in the sample during cooling.

3.2. Experimental investigation of PCM based plasterboard exposed to solar radiation

Next experiments were performed in solar laboratory, which is equipped with solar simulator. In these cases thermal behaviour of plasterboards with PCM were compared to the thermal behaviour of ordinary plasterboard (differential tests).

Two test plate panels (plasterboards) have been made, each of size: 1,000 mm × 500 mm × 15 mm (length, width, thickness). One plate is the composite of gypsum and PCM. Commercial product of BASF Company *Micronal* @ DS 5008 X was used. According to the manufacturer data the melting point is 23^{o}C and heat of fusion equals 110 kJ/kg. The thermal characteristics of Micronal were experimentally verified. PCM and gypsum were mixed in a weight ratio of 0.5533; hence the weight percent of PCM in the composite material was 34.8%. The second plate, as reference plasterboard, was made of gypsum, without doping PCM. Diagram of test plates, with thermocouples location, is shown in Fig. 5.

Temperatures of surface and back sides of test plates were monitored during heating and cooling processes of plates in laboratory conditions. The plates were exposed to insolation of 250 W/m^2, given by solar simulator (Fig. 6).

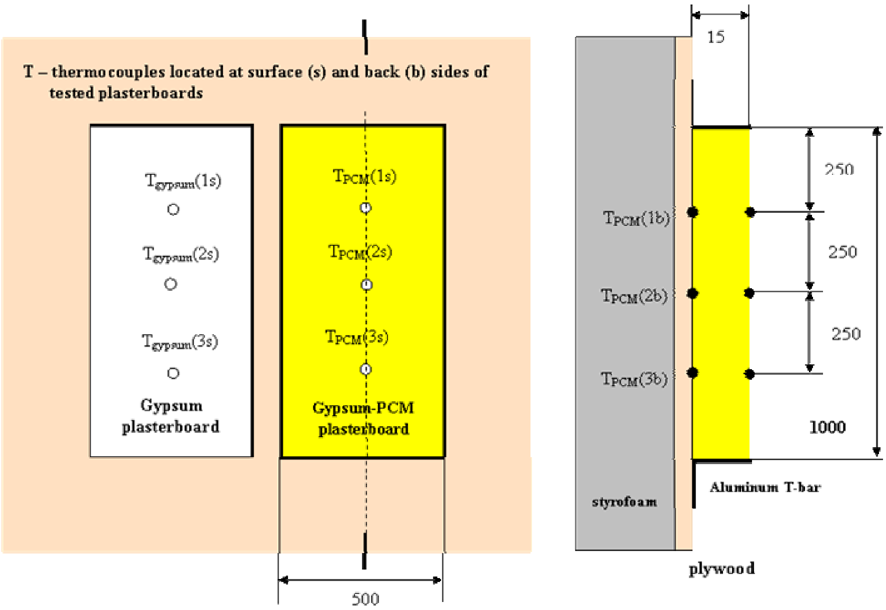

Fig. 5. Test boards: gypsum and gypsum with PCM; dimensions and locations of thermocouples.

Fig. 6. Laboratory stand with test plates – charging process induced by radiation of solar simulator.

A number of successive cycles of heating and cooling processes of test plates were performed. Considering plates as heat storage units charging and discharging processes have been occurred in plates. Each charging process due to solar simulator was lasting few hours, as discharging due to natural convection was lasting a dozen or so hours. During the measurements two plates were subjected to impacts of the same external factors and conditions. The temperature profiles during selected charging and discharging processes are presented below. In Fig. 7 the temperatures profiles and distribution of two plates are shown, obtained during charging process induced by radiation of 250 W/m^2 from solar simulator. The temperatures of reference gypsum plate (both surface and back sides) are significantly higher than PCM based one.

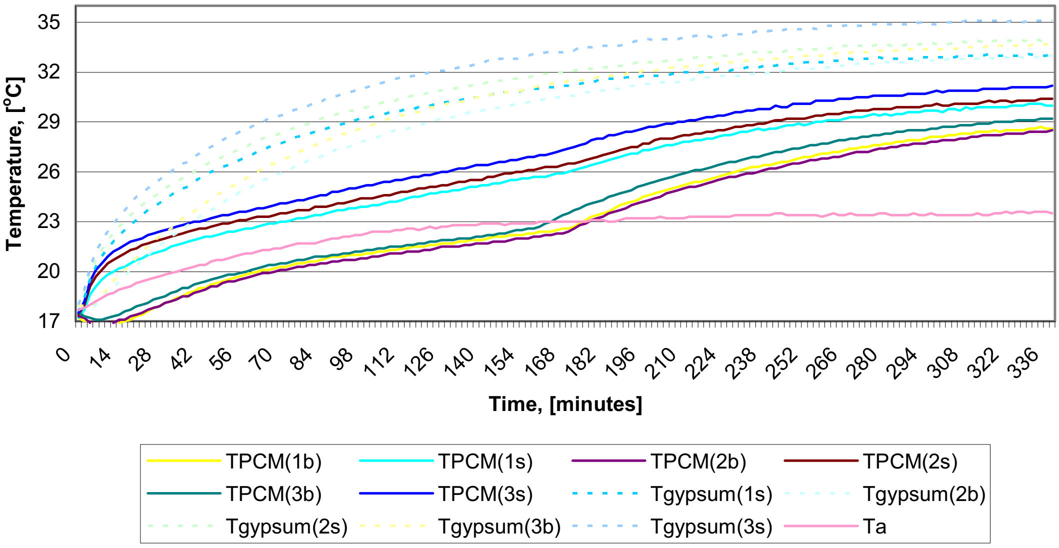

Fig. 7. The profiles of surfaces and back sides temperatures of test panels.

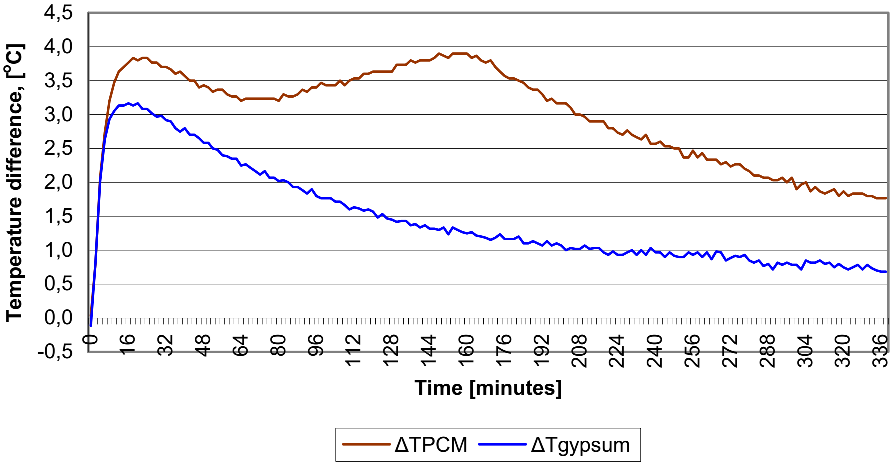

Fig. 8. Differences in average surface and back sides' temperatures of two panels.

In particular the end of the phase transformation process can be identified by PCM temperatures profile analysis. Character of lines is being changed after phase change completion, which occur almost at the same time for PCM plate due to its small thickness. However the temperatures of back side are much higher influenced by phase change. The PCM presence influences the distribution of temperatures along plate thickness. This difference is higher for PCM plate reaching maximum at the end of PCM transition process (Fig. 8).

The typical discharging process of gypsum and PCM-gypsum is shown in Fig 9. The cooling of the plates is caused by natural convection. The phase of PCM solidification could be identified. The phase change process is keeping the temperature level of PCM board at higher level than gypsum board in certain time period.

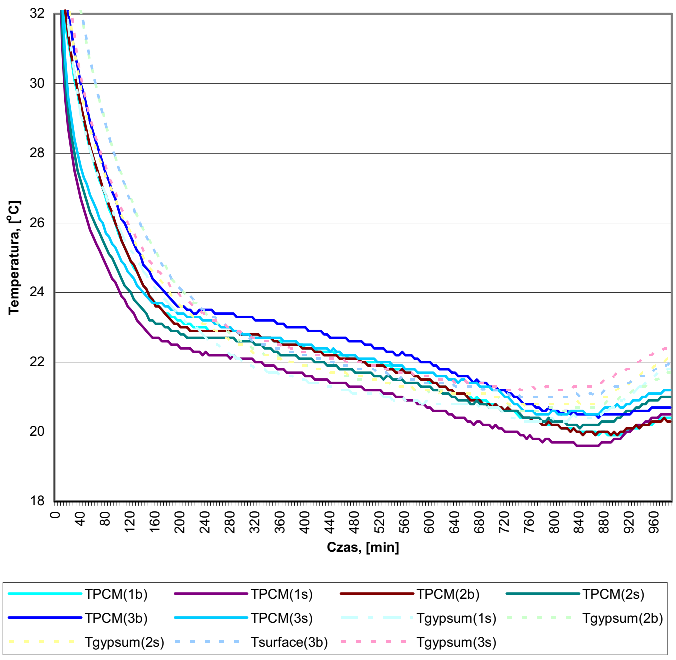

Fig. 9. The course of surface temperature front and rear panels of both test.

The temperatures profiles and distribution in PCM based plasterboard are significantly influenced by the presence of PCM material. In case of performed experiments the PCM was doped in large weight to make the changes compared to the reference plate more visible. PCM material in such quantities, especially in case of the large number of "charging" and "discharging" cycles, causes mechanical destruction of the plasterboard, which effect was observed. PCM material greatly increasing its volume during heating that limits the level of possible PCM fraction in commercial plasterboards. The investigations of mechanical properties of PCM based plasterboards are necessary.

5. Conclusion

Results presented in this paper come from the research project that is focused on the development on new building materials/elements of increased thermal capacity caused by the incorporation of PCMs. Both computer simulation methods and experimental techniques are used in order to achieve the main goals of the project. Using DSC calorimeter thermal capacity characteristics of gypsum-PCM composites were determined, i.e.: functions of enthalpy vs. temperature, enthalpy changes over selected temperature ranges and effective specific heat for a given temperature range. These information are necessary in computer simulation approaches for the analysis of thermal characteristics of energy storage elements. Using the test samples for the measurement of thermal conductivity (by means of plate apparatus) thermal behaviour of gypsum-PCM element in heating and cooling by air in natural convection conditions was investigated. The effect of phase change process (melting and solidifications) of PCM on the air temperature near the sample was clearly visible. Those simple tests showed the potential of plasterboards with PCM to improve the thermal comfort conditions inside rooms. Next experiments were performed with the use of two identical plates; one made of gypsum-PCM composite, the other one made of gypsum only (reference plate). During tests both plates were subjected to solar radiation (heating, charging phase) and cool air in natural convection conditions (cooling, discharging phase). Among others, these experiments gave information on time during which plasterboard under investigation stabilizes temperature in the environment – its characteristics as an energy storage elements. Long time lasting tests also revealed the poor mechanical properties of plasterboards containing high amount of microencapsulated PCM (ca. 35 %).

Acknowledgments

The work was financially supported by Polish Ministry of Science and Higher Education under the grant N N512 459936. Research is a part of international cooperation within the framework of COST Action TU0802 (NeCoE-PCM).

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