The utilization rate of potential heat accumulation capabilities using latent heat of phase-change materials

Anna Zastawna-Rumin1,*, Katarzyna Nowak1

1 Cracow University of Technology, Division Building and Building Physic, Cracow, Poland
* azastawna@pk.edu.pl

Abstract. The aim of the study is to gain information on the actual effects of PCM labor in building partitions. The tested materials were plasterboards containing microcapsules of PCM. Two types of boards with various thermal characteristics of the contained PCM phase change and a simple plasterboard without PCM were tested. The results presented in this paper are one of the few stages of broader research on various PCM materials and different ways of their application. The lightweight wall of timber frame with high thermal insulation was subjected to set of test. The research was conducted in a complex of environmental chambers which allows provide different temperature curve of the chamber possible for real climatic conditions. The temperature and the density of heat flux were the values measured both on the surface and between wall layers. The results of measurements can also serve as a basis to determine the actual thermal characteristics of a partition wall with PCM layers, which can be helpful in creating a design tool to select an appropriate amount of PCM in relation to the thermal load of the building.

1. Introduction
In a situation of constantly increasing requirements of the building users concerning to the heat comfort of rooms, there is a growing emphasis on efficient and affordable in maintenance ways towards reducing excessive heat gain. The applied solutions have to meet the increasingly stringent demands of energy efficiency and be environmentally friendly. Accordingly, it becomes important to use passive solutions which allow to the reduction of buildings’ overheating. The primary solution in this category is the use of thermal mass of the building envelope [1]. Phase change materials (PCM) help to increase partitions’ accumulation potential [2,15].

The results generally relate to the course of temperature change inside a room and on partition surfaces and are often an analysis of a particular case. Few researchers used heat flux measurements and analysis in the context of the amount of accumulated energy [11]. On the other hand, a lot of articles focus on analyzes based on computer simulations [14, 16, 17, 18]. However, the input data for these simulations are usually data obtained by calorimetric research [3,4,5,6]. All these factors are the reason that, despite very high popularity of the subject of PCM, little is known in the articles about the effectiveness of individual solutions and it becomes impossible to compare objectively the degree of utilization of phase-change materials latent heat in various types of described applications.

2. The purpose and scope of the research
The aim of the study is to gain information on the actual effects of PCM labor in building partitions. The tested materials were plasterboards containing microcapsules of PCM. Two types of boards with different thermal characteristics of the contained PCM phase change and a simple plasterboard without PCM were tested. The results presented in this paper are one of the few stages of broader research on various PCM materials and different ways of their application.

The main aim of this analysis was to find answers to these questions:
What real possibilities of energy storage inside buildings has an area unit of surveyed plates, assuming that the heat transfer occurs mainly through natural convection? Is the amount of energy accumulated in the boards sufficient to balance the heat gain inside the room?

To what degree the temperature conditions inside the room affect the use of latent heat of phase change? What is the maximum degree of PCM utilization achievable, assuming very intense cooling during the night?

What scope of phase change temperature results in better use of the material in relation to the expected temperature conditions inside the room?

Due to the main assumptions of the PCM idea, which is based on a significant increase in the accumulation possibilities of building elements without increasing the massiveness of partitions, it seems that a very important information is the amount of heat that can be accumulated in the weight unit of PCM used. Presentation of such results allows to compare theoretical possibilities of a material to those obtained from calorimetry studies. The results will provide information for the use of PCM in relation to its potential.

3. Phase-change materials research in varying temperature conditions

3.1. Measuring post

The research was conducted in a complex of environmental chambers which allows to build a partition with dimensions of 195cm x 210cm and provide different temperature curve on both its sides possible for real climatic conditions. Thanks to partition metering, thermal parameters of individual layers can be registered.

Due to the requirements of energy efficiency for housing buildings, a partition with high thermainsulation was constructed. It is a lightweight wall of timber frame filled with 15-centimeter of polystyrene.

Its inner surface was finished with plasterboard lining. In order to exclude the possibility of air circulation between the thermal insulation and the cardboard, the plate was additionally sealed with silicone around the perimeter.

The partition area was divided into four measuring areas, to which additional layers of materials were attached. Distribution of panels and the equipment used are shown in a diagram in Figure 1.

The research was of a comparative nature; the use of traditional building material (regular cardboard) was the point of reference.

3.2. Equipment

The temperature and the density of heat flux were the values measured both on the surface and between wall layers. On the surface of each of the fixed pads three temperature sensors (K type) and heat meter (of a square shape, with dimensions of 120mm x 120mm) were placed, Fig. 1. Air temperature inside the chambers (at different heights corresponding to the location of heat meters) was measured using temperature sensors Pt 100 and Pt 1000. Measured values were registered via a data collection system Ahlborn Almemo which was connected to a computer. The measurement data were recorded by a data collecting program Data Control 4.2. These data were further processed in Excel. The measurement uncertainty of the tested materials registered surface temperature is influenced by: the resolution of the Almemo system for NiCr-Ni thermocouple (K) and the linear uncertainty of the temperature measurement. The total maximum uncertainty of measurement was 0,12 K.

3.3. Characteristics of the materials

Three cardboard panels measuring 50cm x 60cm were attached to the partition surface. Two of them contained phase-change material and the third was a regular plate without additives. Phase-change material in the two panels was in the form of microcapsules and represented 30% of their weight. Two types of panels were used, with different phase-change material. Thermal characteristics of the used phase change materials have been obtained as the result of calorimetric research.

Plates were placed on one test surface. The plate referred to as PCM 23 was placed next to the plate referred to as PCM 26. The regular plate without addition of PCM was placed below the plate PCM 26.
All the plasterboards were tested for thermal conductivity with Laser Comp Fox 314 meter. The study was conducted for different temperature ranges of heating panels. Selection of a set temperature was dictated by the range of phase change temperature. The results of thermal conductivity are described in the article [19]. The differences in values of thermal conductivity coefficients in this research can be treated as negligible. Parallel placement of plates ensured maintaining identical ambient conditions during measurements and allowing direct comparison of the measured values.

Eighteen different measuring cycles were carried out and their characteristics are listed in Table 1. The duration of each cycle and the temperature changes inside the hot chamber were chosen so that they can comply with the conditions prevailing in the summer and transitional seasons inside insolated premises located within Polish climatic conditions. Each test cycle was separated by breaks used for allowing complete discharging of the boards and stabilization of the conditions.

4. Tests results analysis

Registering indications of heat meters placed on and underneath the surfaces of studied plates allowed plotting graphs of heat density flux for each cycle. An example of such a flux during cycle 0130 is shown in Figure 2a. For the plates containing PCM, a greater heat flux density can be observed on the material surface and a lower density—under the surface in respect to a regular plate. This reflects the increased accumulation possibilities of materials containing PCM in different temperature ranges. Based on these fluxes, graphs were plotted which show the difference in heat fluxes density at each time step. These values provide information about the momentary possibilities of thermal energy storage inside the plates, which can be interpreted as the power of passive cooling element (Fig. 2b). The maximum value is 57.6 W/m².

**Test series A.** For each of the analyzed cycles, courses of the difference in density heat flux over time were integrated showing the amount of accumulated thermal energy (Fig. 3). Air temperature course represents conditions inside premises with a high overheating degree (air temperature reaches 37°C) and a very intense night cooling of 18°C (air temperature of 18°C for at least 9 hours). During these cycles, the tested boards accumulated maximum thermal energy (180.71 Wh/m² for PCM 26 and 162.80 Wh/m² for PCM 23).

**Test series B.** Rooms with a lower degree of overheating (with maximum air temperature at 30°C) and intensive cooling overnight at 18°C (which may be the result of these facilities ventilation with a stream of outside air at night). In these cases, the disparity between the energy accumulated by the panels with significantly different ranges of phase change temperature is surprisingly small.

**Test series C.** The difference in amount of accumulated energy during a seemingly similar cycles 0207, 0207a and 0207b is due to different values of the minimum air temperature inside the chamber (for cycle 0207 it was 22°C, and for cycles 0207a and 0207b it was 28°C). The temperature course inside the chamber is a reflection of the actual indoor temperature course inside public buildings premises during summer season in Poland. The experiment and its results are described in the article [20]. Due to large area of glazing, the room was very overheated (maximum temperature of 36°C). During the first
day, the room was partially ventilated (some windows were open during the night). In the next two days, the windows were not open, which resulted in persistence of high air temperature overnight (28°C). Small amounts of stored energy were the result of such situation (PCM 23 accumulated 2.4 times more energy than a standard board, while PCM 26- 2.6 times more energy). Partial airing of a room results in a significant increase in the amount of energy stored in the boards, especially in PCM 26 (4.5 times more than in a regular panel, PCM 23 only 2.8 times more).

Cycles 0204 and 0204a, from test series B, are characterized by a similar course of air temperature on the side of PCM, while by very different conditions on the outside. Based on these cycles, it can be concluded that the thermal conditions prevailing on the other side of the partition (relative to the position of PCM) do not have much effect on the amount of stored energy.

Test series D represent the course of inside air temperature characteristic for the transition periods (17-24°C). It may seem surprising that the amounts of stored energy, although low, still exceed the amount of the energy stored during the cycle (0207a, b) corresponding to the situation of large interior overheating without night ventilation with external air stream.

Test series E. Slight broadening of the range of air temperature fluctuations inside the chamber (15-28°C) causes a significant increase of stored energy (>100 Wh/m² - PCM 23, 60Wh/m² for PCM 26).

The effectiveness of heat storage in phase-variable materials depends mainly on the heat of phase transformation. Nevertheless, these materials also partially accumulate heat in an explicit way. It has been assumed (in accordance with the technical specification of the material) that the PCM used has an explicit specific heat of 1.2 kJ / kg·K. Taking this value into account, the amount of energy stored in the explicit way was estimated. This value was subtracted from the total amount of energy stored by the examined materials in order to be able to assess the actual share of phase transitions in the accumulation process. The amount of accumulated energy calculated in this way was compared to the results obtained from calorimetric studies.

| Test series | No. | Cycle name | Temperature range inside the hot chamber (°C) | Temperature range inside the cold chamber (°C) | Cooling time before the cycle [h] | Cooling time during the cycle [h] | Cooling time after the cycle [h] | Total time of cycle duration [h] |
|-------------|-----|------------|---------------------------------------------|------------------------------------------------|----------------------------------|-------------------------------|-------------------------------|-------------------------------|
| A           | 1   | 0129       | 18-37                                       | 18-37                                          | 12                               | 3.5                           | 4                             | 12                            | 18                            | 12                            |
|             | 2   | 0121       | 16-36                                       | 16-36                                          | 14                               | 0                             | 7                             | 7                             | 14                            | 18                            | 14                            |
|             | 3   | 0130       | 18-36                                       | 18-36                                          | 12                               | 4                             | 4.5                           | 4.5                           | 9                             | 18                            | 13                            |
| B           | 4   | 0131       | 18-30                                       | 18-30                                          | 12                               | 4                             | 3                             | 3                             | 12                            | 18-46                          | 10                            |
|             | 5   | 0131a      | 18-30                                       | 18-30                                          | 12                               | 4                             | 3                             | 3                             | 12                            | 18-46                          | 10                            |
|             | 6   | 0131b      | 18-30                                       | 18-30                                          | 12                               | 3.5                           | 3                             | 3                             | 12                            | 16-32                          | 10                            |
|             | 7   | 0203       | 18-30                                       | 18-30                                          | 12                               | 3.5                           | 3.5                           | 3.5                           | 12                            | 16-32                          | 10                            |
|             | 8   | 0204       | 18-30                                       | 18-30                                          | 12                               | 3.5                           | 3                             | 3.5                           | 12                            | 16-44                          | 10                            |
|             | 9   | 0204a      | 18-30                                       | 18-30                                          | 12                               | 3.5                           | 3                             | 3.5                           | 12                            | 16-44                          | 10                            |
| C           | 10  | 0207       | 22-36                                       | 22-36                                          | 12                               | 5                             | 10                            | 7                             | 5                             | 21                            | 22                            |
|             | 11  | 0207a      | 28-36                                       | 28-36                                          | 5                                | 5                             | 7                             | 7                             | 5                             | 21                            | 19                            |
|             | 12  | 0207b      | 28-36                                       | 28-36                                          | 5                                | 5                             | 7                             | 7                             | 5                             | 21                            | 19                            |
| D           | 13  | 0210       | 17-24                                       | 17-24                                          | 8                                | 4                             | 9                             | 9                             | 8                             | 22                            | 22                            |
|             | 14  | 0210a      | 17-24                                       | 17-24                                          | 8                                | 4                             | 9                             | 9                             | 8                             | 22                            | 22                            |
|             | 15  | 0212       | 17-24                                       | 17-24                                          | 8                                | 3                             | 8                             | 12                            | 12                            | 20                            | 23                            |
| E           | 16  | 0214       | 15-28                                       | 15-28                                          | 12                               | 4                             | 4                             | 4                             | 12                            | 20                            | 12                            |
|             | 17  | 0214a      | 15-28                                       | 15-28                                          | 12                               | 4                             | 4                             | 4                             | 12                            | 20                            | 12                            |
|             | 18  | 0214b      | 15-28                                       | 15-28                                          | 12                               | 4                             | 4                             | 4                             | 12                            | 20                            | 12                            |
5. Conclusion

With very good cooling conditions during the night and high air temperatures during the day (cycles 0121, 0129, 0130), i.e. ideal conditions for activating PCM, the ratio of the actual accumulated energy to the amount predicted from calorimetric tests was over 96% for PCM 26 and over 88% for PCM 23. These are the highest results obtained during the research, i.e. the potential capabilities of PCM are the best when used in these conditions.

In the case of intensive night cooling and slight overheating (cycles 0131, 0131a, 0131b, 0203, 0204, 0204a), PCM utilization is 70% - 83% for PCM 23 and 77% - 83% for PCM 26. In the case of temperature conditions possible for transition periods (0210, 0210a, 0212), when the maximum temperature reaches only 26 °C, the use of the storage capacities of the phase transformations is more strongly diversified. In the case of PCM 23 it is in the range of 23.5% - 35.6%, and in the case of PCM 26 it is only 10.5% - 17.4%. The extension of the temperature range (cycles 0214, 0214a, 0214b) results in a significant increase in the efficiency of using PCM. In particular, this applies to PCM 23 (increase in use up to 61%).

Strong overheating without cooling the partitions (cycles 0207a and 0207b) results in very low PCM capacity - only 5%.

The analysis of temperature data of the outdoor air in the city of Kraków indicates that the temperature below 20° C can occur for over 90% of the analyzed time. Thus, it is possible to use the external air stream to cool the room to a level that enables solidification of the PCM contained in the boards. The condition, however, is the actual possibility of intensive cooling of the room being used in the analyzed time interval. Providing the conditions necessary to discharge energy is therefore a key requirement for the effective operation of PCM.

Analyzing only the process of heating the partition, PCM 23 may seem a potentially more beneficial solution than PCM 26. However, the choice of PCM 26 gives a higher probability of full release of stored energy, which in the long run can guarantee greater efficiency than PCM 23. Therefore, it is suggested to use PCM 23 in objects where it is possible to very intensive cooling of the room by
Figure 3. The amount of thermal energy accumulated during individual cycles [Wh/m²].

ventilation or mechanical ventilation. First of all, it is possible in buildings in which people do not stay during the night. In facilities where it is impossible to very intense night ventilation, such as objects permanently inhabited by people, it is suggested to use PCM 26.

References

[1] M. Santamouris and D. Kolokotsa, “Passive cooling dissipation techniques for buildings and other structures: The state of the art”, Energy Build., vol. 57, pp. 74–94, 2013.

[2] A. Zastawna-Rumin, K. Nowak, “Experimental Thermal Performance Analysis of Building Compo-nents Containing Phase Change Material (PCM)”, Procedia Eng., vol. 108, pp. 428–435, 2015.

[3] J. P. Dumas, S. Gibout, L. Zalewski, K. Johannes, E. Franquet, S. Lassue, J. P. Bédécarrats, P. Tittelein, and F. Kuznik, “Interpretation of calorimetry experiments to characterise phase change materials”, Int. J. Therm. Sci. vol. 78, pp. 48–55, 2014.

[4] C. Rathgeber, L. Miró, L. F. Cabeza, S. Hiebler “Measurement of enthalpy curves of phase change materials via DSC and T-History: When are both methods needed to estimate the behaviour of the bulk material in applications?”, Thermochimica Acta, vol. 59, pp. 79-88, 2014

[5] A. Lazaro, C. Peñalosa, A. Solé, G. Diarce, T. Haussmann, M. Fois, B. Zalba, S. Gishwander, and L. F. Cabeza, “Intercomparative tests on phase change materials characterisation with differential scanning calorimeter”, Appl. Energy, vol. 109, pp. 415–420, 2013.

[6] E. Günther, S. Hiebler, H. Meiling, and R. Redlich, “Enthalpy of Phase Change Materials as a Function of Temperature: Required Accuracy and Suitable Measurement Methods”, Int. J. Thermophys., vol. 30, no. 4, pp. 1257–1269, 2009.

[7] K. Athienitis, “Investigation of the Thermal Performance of a Passive Solar Test-Room with Wall Latent Heat Storage”, vol. 32, no. 5, 1997.

[8] L. Shilei, Z. Neng, and F. Guohui, “Impact of phase change wall room on indoor thermal environment in winter”, Energy Build., vol. 38, no. 1, pp. 18–24, 2006.

[9] S. Scalat, D. Banu, D. Hawes, J. Paris, F. Haghighata, and D. Feldman, “Full scale thermal testing of latent heat storage in wallboard”, Sol. Energy Mater. Sol. Cells, vol. 44, pp. 49–61, 1996.

[10] L. Shilei, F. Guohui, Z. Neng, and D. Li, “Experimental study and evaluation of latent heat storage in phase change materials wallboards”, Energy Build., vol. 39, pp. 1088–1091, 2007.

[11] P. SCHLOSSIG, H. HENNINGS, G. SCHWANDER, and T. HAUSSMANN, “Micro-encapsulated phase-change materials integrated into construction materials”, Sol. Energy Mater. Sol. Cells, vol. 89, no. 2–3, pp. 297–306, 2005.

[12] F. Kuznik and J. Virgone, “Experimental assessment of a phase change material for wall building use”, Appl. Energy, vol. 86, no. 10, pp. 2038–2046, 2009.

[13] C. Voelker, O. Kornadt, and M. Ostry, “Temperature reduction due to the application of phase change materials”, Energy Build., vol. 40, no. 5, pp. 937–944, 2008.

[14] Y. Dutli, D.R. Rousse, N. Ben Salah, S. Lassue, L. Zalewski, “A review on phase-change materials: Mathematical modeling and simulations”, Renew. Sustain. Energy Rev., vol. 15, no. 1, pp. 112–130, 2011.

[15] F. Kuznik, D. David, K. Johannes, and J.-J. Roux, “A review on phase change materials integrated in building walls”, Renew. Energy Rev., vol. 15, no. 1, pp. 379–391, 2011.

[16] S. N. AL-Saadi and Z. (John) Zhai, “Modeling phase change materials embedded in building enclosure: A review”, Renew. Sustain. Energy Rev., vol. 21, pp. 659–673, 2013.

[17] L. F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, and A. I. Fernández, “Materials used as PCM in thermal energy storage in buildings: A review”, Renew. Sustain. Energy Rev., vol. 15, no. 3, pp. 1675–1695, 2011.

[18] F. Kuznik J. Virgone, “Experimental investigation of wallboard containing phase change material: Data for validation of numerical modeling”, Energy Build., vol. 41, no. 5, pp. 561–570, 2009.

[19] K. Nowak., A. Zastawna-Rumin., “Badanie i analiza przegrody z dodatkiem materiałów fazowo zmiennych w warunkach niestacjonarnych.” Fizyka Budowl w Teorii i Praktyce Łódź 2013 s.291-296, ISBN 978 – 83 – 936869 – 1 – 9.

[20] A. Zastawna-Rumin, K. Nowak, “Badanie przegrody zawijającej materiał fazowo zmienny w warunkach w situ”. Czasopismo Inżynierii Lądowej, Środowiska i Architektury = Journal of Civil Engineering, Environment and Architecture : JCEEA. – 2015, t. 32, z. 62 (2/15), s. 595-602.