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# Experimental Investigation of the Impact of PCM Containment on Indoor Temperature Variations

Iva Rešetar[1*], Norbert, Palz[1]

[1]Berlin University of the Arts, Institute for Architecture and Urban Planning

[*]*Corresponding email: i.resetar@udk-berlin.de*

**ABSTRACT**

In view of growing concerns on climate change and temperature extremes, there is a need to explore novel methods that provide thermal comfort in architecture. Latent heat thermal energy storage with phase change materials (PCM) has been widely researched in last decades in the field of energy technology and proved beneficial for reduction and shifting of the thermal loads and improving the overall thermal storage capacity of building components. Although a variety of PCM containments have been investigated for indoor cooling applications, the examples of exposed, design-oriented macro-encapsulations are rare.

This paper presents a study of visible, suspended ceiling encapsulations for passive cooling, made of glass and novel bio-based PCM. The aim is to provide an overview of correlations between basic containment geometries and their thermal behavior that serves as a base for the further design of custom-made PCM macro-encapsulations. An experimental set-up of test boxes is developed for thermal cycling and a comparative analysis of the thermal performance of varied PCM encapsulation geometries. The study concludes that the containments with the large exchange surface and the small thickness offer an optimal material distribution for the temperature reduction in the box. Based on experimental results, suggestions are made on further formal strategies for the design of cooling elements for local thermal regulation.

KEYWORDS

Phase change materials, passive cooling, containment geometry, thermal cycling, glass macro-encapsulation

## INTRODUCTION

Contemporary buildings increasingly rely on centralized mechanical systems for the indoor climate control, due to the low thermal inertia and high energy gains in buildings. A promising renewable energy alternative that could decrease the dependency on high-energy consuming technologies and improve the thermal stability of buildings is the latent thermal energy storage with PCM (Kośny, 2015; Zalba et al., 2003).

Current advancements in materials science and the growing interest of designers in a material-driven performance are opening a possibility for architectural elements to take a more active role in managing thermal environments (Addington and Schodek 2005; Bechtold and Weaver 2017). PCM belong to the novel class of property-changing materials with an inherent capacity for thermoregulation, as they can dynamically exchange the energy with surroundings while changing the phase at a desirable temperature. Although the primary goal of the implementation of PCM is to achieve energy savings in buildings, PCM present yet unrealized potential for architectural design and an opportunity for new design methodologies based on their thermodynamic behavior.

PCM are substances capable to absorb, store and release a large amount of energy in the form of latent heat during melting and solidification at a certain, predictable temperature. PCM act as latent thermal energy storage due to their large phase change enthalpy or latent heat of fusion. Unlike the sensible heat storage, where the added heat results in the temperature increase of the storage medium, the latent heat storage medium remains at almost constant temperature throughout the solid-liquid phase transition. The added heat is gradually absorbed by the material till the melting is complete and released when the surrounding temperature drops, and the material starts to solidify (Mehling and Cabeza, 2008). In that way, PCM operate in thermal cycles responding to local temperature fluctuations and can be used repeatedly without material degradation.

In passive or free cooling applications, PCM takes advantage of diurnal temperature differences, releasing the coldness stored during the night when, during the day, the indoor temperature rises above the comfort zone (Raj and Velraj, 2010). Currently available PCM products for passive cooling span from micro-encapsulations integrated in different building materials to macro-encapsulated elements placed behind the suspended ceiling. However, for PCM to function efficiently and regenerate during the night, a direct contact with the cold air (heat sink) is of advantage. This study therefore proposes visible suspended glass encapsulations that support recharging of the PCM by night ventilation. Since PCM has a low thermal conductivity, the containment geometry plays an important role for managing the heat transfer between the PCM and surroundings. Thus, coupling the basic encapsulation geometries with their thermal behavior in this paper aims to widen the range of PCM encapsulations and outline their use within the design realm.

## METHODS

To evaluate the impact of varied PCM encapsulations on the indoor temperature, an experimental set-up for thermal cycling with test boxes was developed. Previous experiments that used test boxes to access the thermal performance of the composite PCM wall are described in literature (Kuznik and Virgone, 2009). Similarly, in this study two identical boxes – a test box containing the PCM sample and an empty reference box – were placed next to each other in a controlled indoor environment and exposed to thermal excitation. Boxes were made of plywood 18mm, covered with 30mm insulation panels, with the glazed front that allowed irradiation by two halogen 750W lamps placed in the front (Fig. 1).

a) b)

Figure 1. Experimental set-up for thermal cycling. a) Test boxes, b) Tubular encapsulations.

The temperature differences were observed during two subsequent heating (3h) and cooling (6h) cycles of total duration of 18h. During heating cycle, the temperature in the boxes oscillated from 17◦C to 30◦C, with a resulting heat rate slightly above of the average due to the direct solar irradiation of buildings in the summer. The cooling cycle corresponded to the effect of night cooling needed for the PCM regeneration. The instrumental set-up consisted of two 176T2 dataloggers with four Pt-100 glass-coated probes of the class A precision, measuring air, PCM and the room temperature in the interval of 1 minute. Thermal camera was attached at the bottom of the box, capturing surface temperatures every 30 minutes. A reflective shield protected air probes from the direct irradiation. Before commencing measurements, several calibration cycles with different positions of probes were done and showed no temperature gradients in the box, and the temperature differences within tolerance values (0.2◦C).

Table 1. Physical properties of bio-based PCM from the data sheet of the producer.

| Property | Values |
|---|---|
| Melting / crystallization temperature | 21◦C / 19◦C |
| Latent heat | 190 KJ/kg |
| Specific heat capacity solid / liquid | 2.1 kJ/(kg·°C) / 2.3 kJ/(kg·°C) |
| Thermal conductivity solid / liquid | 0.18 W/(m·°C) / 0.15 W/(m·°C) |
| Density solid / liquid | 891 kg/m3 / 850 kg/m3 |

The material used in the study belongs to the novel bio-based category of PCM, with a low melting temperature suitable for indoor applications (Tab. 1). The choice of the containment geometries was made according to the standard typologies described in the literature (Mehling and Cabeza, 2008; VDI, 2016). A total volume of 500ml of PCM was used in each measurement, either in a single containment or divided into five smaller units of 100ml. Encapsulations were made of borosilicate or soda-lime glass of approx. thickness 2mm in following formats: spherical containments used standard laboratory 500ml and 100ml glass flasks; multiple tubular used standard 100ml test tubes; 500ml tube was produced by lampworking technique; flat container was produced by modifying a standard petri dish ⌀ 180mm.

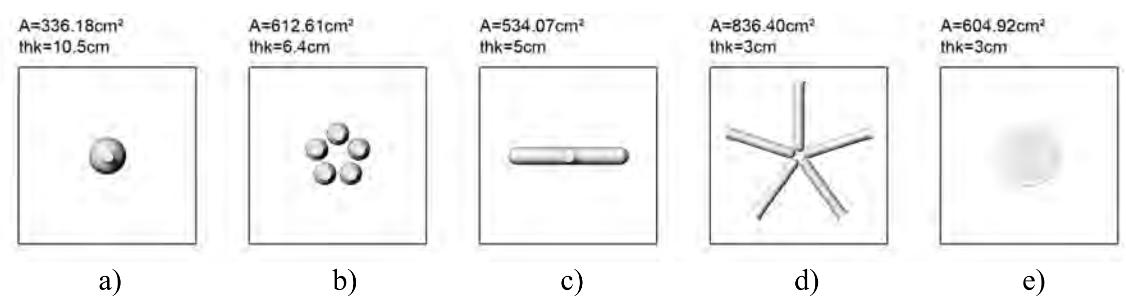


Figure 2. Ground plan of the box with containment geometries showing surface area and max. thickness. a) Sphere 500ml, b) Multiple spheres 5x100ml, c) Tube 500ml, d) Multiple tubes 5x100ml, e) Flat plate containment 500ml.

**RESULTS**

The graphs show a characteristic latent heat thermal storage effect with a temperature plateau during the melting phase of the material (Fig. 3). All encapsulations except the 500ml spherical and flat containments allowed the full melting of the PCM. The multiple tubular geometry caused the biggest temperature differences between the test boxes (Tab. 2 and Fig. 3) and allowed the largest portion of the material to recharge during the cooling cycle in comparison to other containments (Fig. 4).

**Tables and illustrations**

Table 2. Temperature differences in boxes in relation to geometry.

| Encapsulation geometry | Values 1st/2nd cycle |
|---|---|
| a) Sphere 500ml | 1.15◦C / 1.13◦C |
| b) Multiple spheres 5x100ml | 1.64◦C / 1.62◦C |
| c) Tube 500ml | 1.51◦C / 1.48◦C |
| d) Multiple tubes 5x100ml | 2.04◦C / 2.03◦C |
| e) Flat containment 500ml | 1.41◦C / 1.50◦C |

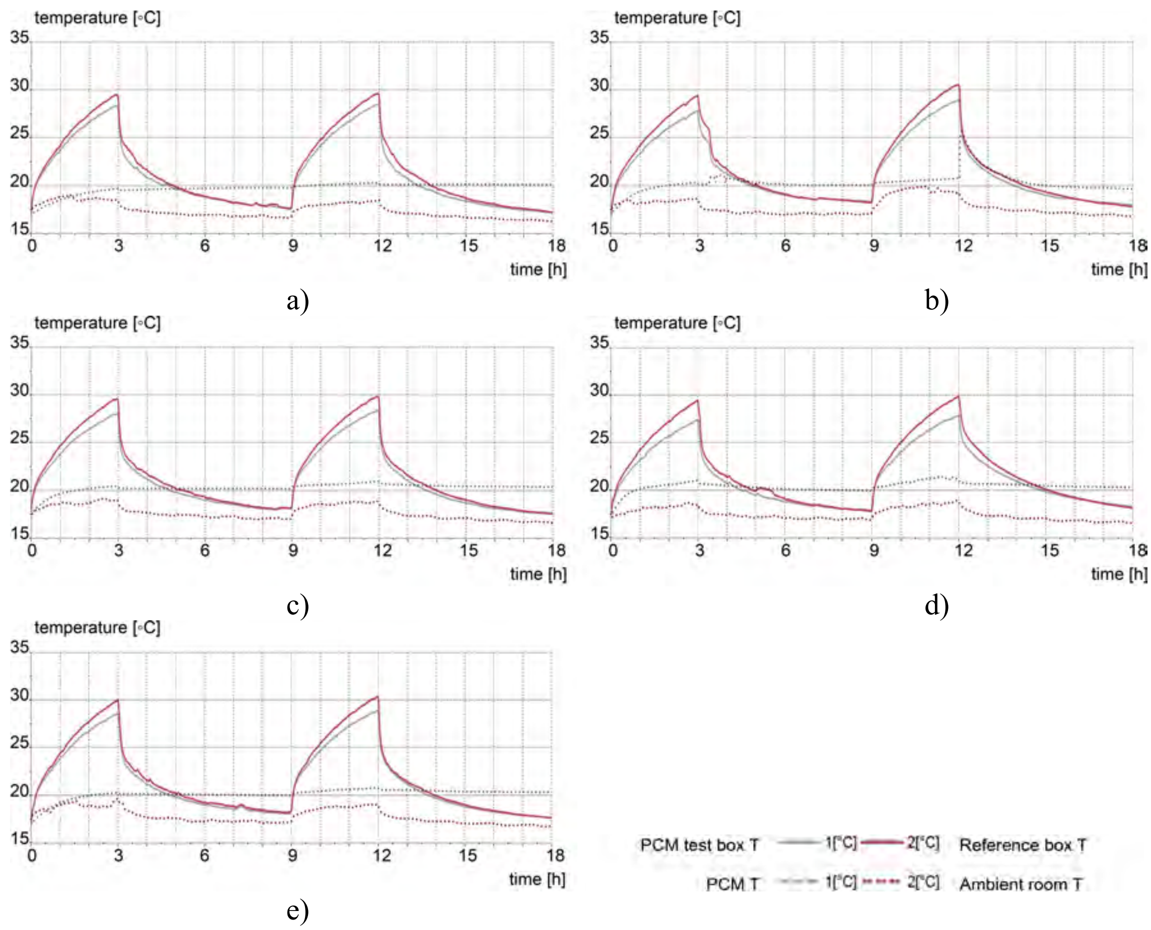


Figure 3. Impact of PCM on temperature reduction in the box. a) Spherical containment, b) Multiple spherical containment, c) Tubular containment, d) Multiple tubular containment, e) Flat plate containment.

**DISCUSSIONS**

Multiple containments improved the cooling effect of the single ones by 40%. The results point out to benefits of increasing and differentiating surfaces that enclose a certain volume. Although the exhibited differences of the cooling potential between PCM containments are small, it is expected that they gain on importance in the design of larger ceiling systems. Measurements in real conditions with actual thermal loads, building materials and occupant behaviour are, however, necessary to validate these findings. Regarding the orientation of encapsulations, the experiments assumed the horizontal position of tubes and flat containers optimal for the uniform temperature distribution and steadily moving melting fronts (Khan et. al, 2016).

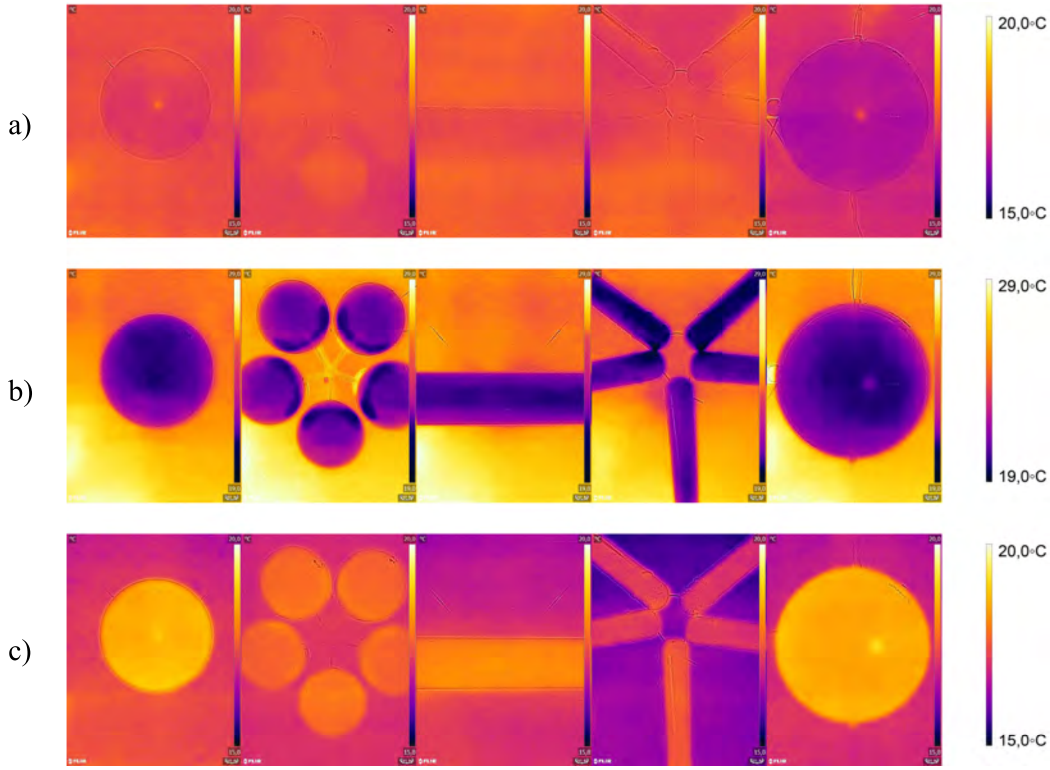


Figure 4. Thermographic images showing surface temperature at the beginning and the end of the heating and cooling cycle: a) 0h, b) 3h, c)12h.

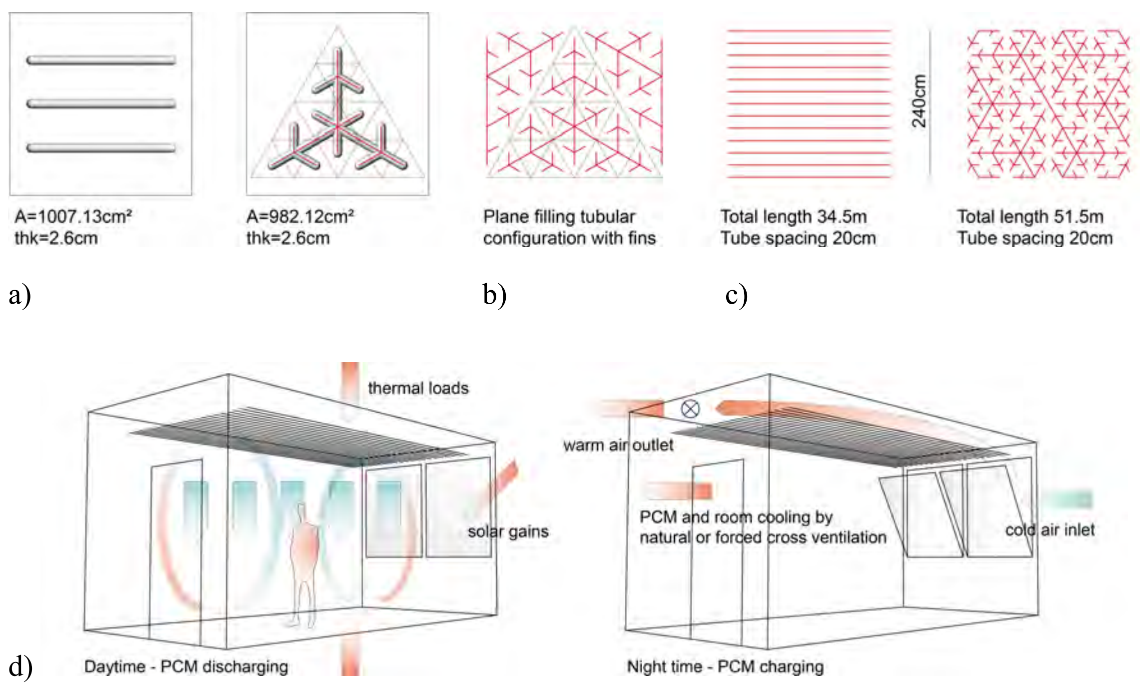


Figure 5. a) Linear and plane filling tubular elements of 2.6cm thickness and 500ml volume in the test box, b) Plane filling configuration principle, c) Difference between linear and plane filling patterns in material distribution in larger space, d) Diagram of the operating principle of the PCM cooling ceiling made of suspended glass elements.

A further increase of the surface area of tubular encapsulations could be achieved by introducing elements with fins (Fig. 5a), and by formal strategies for connecting elements into larger systems, such as plane or space filling tree configurations (Fig. 5b). Compared to linear configurations (VDI, 2016), these branching structures could provide a large and uniform material distribution with an increased element spacing (Fig. 5c) necessary for recharging the material during the night by convection and conduction (Fig. 5d).

## CONCLUSIONS

This work presented investigation of thermal performance of spherical, tubular and flat plate glass encapsulations containing novel bio-based PCM. An experimental set-up of the test box was developed for the comparative analyses of the impact of the encapsulation geometry on the indoor temperature in the test box. Single and multiple units of an equal volume, but varying surface and thickness were tested, and the effect of the increased surface and reduced thickness on temperature reduction was observed. Temperature measurements reflected the differences in the volume-surface ratio of containments and showed the biggest reduction of 2◦C in the box with multiple tubular PCM encapsulations. The paper concludes that new design and recharging opportunities for cooling ceilings could be afforded by the exposed glass encapsulations and suggests further formal strategies for increasing the surface area while keeping the thickness, volume and spacing of the encapsulation elements at optimum. These findings on cooling effects of glass encapsulations can inform the concept phase of the design of more elaborate custom-made ceiling elements for local thermal regulation.

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