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Dynamic thermal performance of a PCM window system: characterization using large scale measurements

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Abstract

Introduction of more dynamic building envelope components have been done throughout the last decades in order to try to increase indoor thermal comfort and reduce energy need in buildings for both temperature and light control. One of these promising technologies is phase change materials (PCM), where, the latent heat storage potential of the transition between solid and liquid state of a material is utilized as thermal mass. A PCM layer incorporated in a transparent component can increase the possibilities to harvest energy from solar radiation by reducing the heating/cooling demand and still allowing the utilization of daylight. The introduction of dynamic components in the building envelope makes the characterization of conventional static performance indices insufficient in giving a clear picture of the performance of the component in question.

Measurements have been performed on a state-of-the-art window that integrates PCM using a large scale climate simulator. The glazing unit consists of a four-pane glazing with an integrated layer that dynamically controls the solar transmittance (prismatic glass) in the outer glazing cavity. The innermost cavity is filled with a phase change material.

This article presents and assesses the series of measurements and the related methodologies with the aim of investigating the thermal behavior and thermal mass activation of the PCM-filled window. The experiments have been carried out using several static and dynamic test cycles comprised of temperature and solar radiation cycling. A conventional double-pane window has also been experimental investigated using the same test cycles for reference purpose.

It was found that even for temperatures similar to a warm day in Nordic climate, the potential latent heat storage capacity of the PCM was fully activated, but relatively long periods of sun combined with high exterior temperatures are needed.

Keywords: window, façade, phase change material, experimental, measurement, dynamic, climate simulator.

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1. Introduction

In recent years there has been an increasing interest in, and amount of research carried out regarding fairly new technologies like Phase Change Materials (PCM). A PCM in a building context is a material that has a melting point in the region close to the comfort or operational temperature in the building where it is adopted. The latent heat storage potential in the phase transition between liquid and solid state can thus be utilized as heat storage and shows a favorable behavior in terms of increasing the thermal inertia of the system. The aim of including a PCM layer into a transparent system is to collect (a large part of) the NIR solar radiation (that does not contribute to daylight) within the PCM layer itself and letting (the largest part of) the visible solar radiation enter the indoor environment, thus still allowing natural light exploitation for daylighting purposes. This behaviour is achieved thanks to the highly selective optical properties of (paraffin wax based) PCM – optical characteristics of a simple window system with PCM (paraffin) can be found in [1]. A more thorough literature and technology overview is given by Grynning et al. [2], while information of spectral properties of other types of PCM (e.g. salt hydrates) can be found in [3].

Performing measurements on dynamic systems, like the PCM glazing, is extremely relevant. The complex interaction of solar radiation and phase change has a complicating effect on the physical behavior of such a system. Characterizations that make use of only analytical and numerical tools are well known to be difficult and should be subject to experimental validation. Full scale testing can thus serve as validation support for the theoretical models that are being developed. An example of this procedure can be found in [4]. The use of a full scale climate simulator, where temperatures and solar irradiance levels can be dynamically regulated and controlled, increases the possibilities to deepen the investigation on the behavior of a translucent component under defined environmental conditions. Comparative measurements on a reference window with well-known properties have also been carried out, where a window with a double-pane insulated glazing unit (IGU) was subject to the same test cycles as the PCM window and the same parameters were measured.

2. The PCM and reference windows

Measurements have been carried out on a commercially available glazing system with an integrated prismatic solar reflector and a PCM filled cavity (also described as GlassX in this paper). The producers have not stated the amount of PCM in the window, but the thickness of the PCM encasings were measured to be approximately 23 mm thick. The type of glazing system has been used in several existing buildings, primarily in Switzerland, and the PCM glazing is often combined with standard windows in the façade.

The window used for the experiment is a 1.2 m by 1.2 m large window which consists of a four-pane glazing package A solar reflection device, i.e. a prismatic polymer layer [5] is placed in the outermost cavity. The aim of the prismatic reflector is to provide a seasonal-dependant direct transmission of impinging solar radiation (with angles lower than 35 °, radiation is transmitted; with angles higher than 45 °, i.e. angles of incidence higher than the critical angle of total reflection, radiation is reflected by the rear surface of the prismatic pane). The second cavity is argon-filled and has one low-emission coating. The innermost cavity hosts a salt hydrate PCM in a polycarbonate vessel.

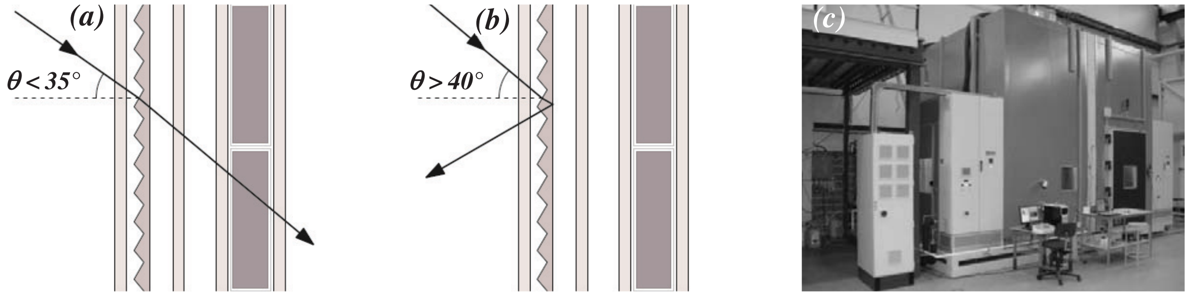

Fig. 1. (a-b) vertical cross sections of the PCM window [6], with illustration of the angular properties of the solar reflection device in the outer cavity: (a) radiation with low incidence angles (typical winter days) is transmitted, (b) high-angle incident radiation (typical summer days) is reflected; (c) the climate simulator used for the PCM-glazing and reference window measurements.

Table 1. Declared and measured thermal and optical values of the PCM glazing [6,7]. The value of α (in the measured values columns), show the angle of incident light.

	Declared values [6]			**Measured visual transmittance values** [7]		
	U-value (W/m²K)	g-value (-)	T_{vis} (-)	Direct - diffuse α = 0	Direct - diffuse α = 30	Diffuse – diffuse
PCM Solid state	0.5	0.33 ± 4 %	0.08 – 0.24 (± 3 %)	0.21	0.19	0.17
Liquid state		0.37 ± 4 %	0.12 – 0.44 (± 3 %)			
Reference window	1.2[1]	0.63[2]	0.80[2]			

[1] *Measured according to EN-ISO 12567* [8]

[2] *Declared values from producer of glazing unit* [9]

A cross-section of the PCM window is shown in Figure 1, with a schematic illustration of the working principle of the prismatic reflector. The window optical and thermal properties are reported in Table 1.

It is important to highlight that, due to the structure of the glazed unit (which incorporates a prismatic pane and PCM encapsulated in a polycarbonate vessel), transmission of visual information is never assured, i.e. the glazing appears as a mostly diffusive medium and the view through it is not possible. From one point of view, this behaviour can be considered a drawback, on the other side the lack of a significantly different appearance between the solid and liquid phase of the PCM (as seen in other glazing configurations, e.g. [10]) can be also seen as a positive feature.

3. Test methods and measurement equipment

3.1. The climate simulator and instrumentation of samples

Measurements presented in this paper have been performed by means of a state-of-the-art climate simulator. This facility allows climatic conditions on both sides of the building component sample to be dynamically controlled according to the desired schedule. The climate simulator is composed of two separated chambers, and the sample to be tested is installed between them. Fig. 1c shows the climate simulator. In the outdoor chamber, the air temperature can be controlled in the range -20 to +80 °C and relative humidity in the range 20 to 95 %. Both rain and solar irradiation can be simulated, by a water nozzle system and a solar simulator, respectively. The solar simulator is made of nine xenon lamps arranged in a 3 x 3 matrix, which can emit, evenly distributed over the entire sample area, up to 1 kW/m^2 (the integral value over the full spectrum). The spectral emissivity of the lamp is as close as possible to that of the sun. The lamp matrix is placed parallel to the tested sample at 1 m distance. Each lamps can be switched on and off individually and the power emission can be further tuned step-less down to 50 % of the maximum level of 1 kW/m^2. It is important to underline that the radiative flux from the lamp matrix is homogenous over the entire sample, thus making impossible to differentiate between direct and diffuse radiation (the entire radiation is direct, with the propagation vector perpendicular to the sample). This feature limits the possibility to study the influence of solar irradiation to energy-related aspects only, avoiding any influence of geometric factors (such as beam angle or direct-to-diffuse ration).

The indoor air temperature and relative humidity (RH), in the (opposite) chamber that simulates the indoor temperautre can be varied within a range +5 to +50 °C and the RH between 20 and 95 %, respectively. The test chambers and HVAC system are designed so that temperature distribution inside each test chamber is as uniform as possible. However, concerns may arise as far as the temperature field in the air space between the lamp array and the sample is concerned, since convective heat exchange between air and xenon lamps cannot be excluded.

Measures were in particularly taken in the test facility so that this disturbance is limited: the lamps are located far enough from the sample in order to have a significant air layer between the solar simulator and the sample; the air-change rate in the chamber that hosts the solar simulator is high in order to ensure sufficient ventilation in the gap between the lamps and the sample.

The instrumentation of the two tested glazing systems included: 10 T-type thermocouples (five on each side) evenly distributed on the specimen and at different levels; four heat flux meters placed at two different levels on the inside surface of the glazing; two pyranometers, parallel to the glazing, one on the outside and one on the inside of the sample. More information about instrumentations and accuracy can be found in [2].

3.2. Measurement test cycles

Although the experimental facility is able to dynamically change the outdoor (and indoor) boundary conditions, tests carried out in this part of the research activity have focused on stationary boundary conditions. In one aspect, this approach will not allow the most relevant (dynamic) features of advanced systems to be fully exploited and evaluated. It will, however, give fundamental assessment of the thermophysical and optical behaviour of such systems. Starting from the gained knowledge of steady-state performance, future experiments are planned to deepen the understanding of the performance under a transient regime.

In the experiments herewith presented, the main focus is placed on the influence of solar irradiance on the PCM layer, combining different short-wave radiation fluxes with thermal gradients and temperature levels. In particular, Test 1-6 were carried out with outdoor and indoor temperature of 24 °C. Pulsed solar irradiation levels were set to 1 kW/m² for series 1-3, with pulse duration of 1, 2 and 4 hours for series 1, 2 and 3 respectively. Irradiance level was set to 0.5 kW/m² for series 4-6, with pulse duration of 2, 4 and 8 hours, for series 4, 5 and 6 respectively. These tests were carried out in order to study the influence of the solar irradiation in a temperature range close to the transition phase without the contribution of a thermal gradient between outdoor and indoor. Test 7-9 present a thermal gradient (20 °C indoor temperature and 10 °C outdoor temperature) between the two chambers and short-wave radiation pulses, giving a picture of combined mechanisms related to different stresses.

4. Results and discussion

For the first two cycles, as shown in Figure 2, it is possible to see that the temperature increase for the indoor measuring points of the PCM glazing system follow a smooth exponential development, thus indicating that the phase change dynamics of the glazing have been activated and heat transmission towards the indoor environment is reduced by the utilization of the system's high heat capacity. However, for the third cycle where the duration of the solar stress was four hours, the increase of the indoor surface temperature has a larger gradient for the latter part of the period. This, more linear, temperature development indicates that the phase transition temperature of the PCM has been completed and the internal temperature of the PCM increases undisturbed by the (already utilized) latent energy storage effects of the phase transition. When the solar stress comes to an end, the initial temperature drop is fast, but the latter temperature decrease follows a less steep evolution, further confirming that the thermal inertia given by the latent heat of fusion of the PCM has been fully activated. By the analysis of the change in the temperature development's slope it can be inferred that the phase change is completed when the PCM-window's surface temperature is around 28.5 °C. The reference window has identical temperature propagation for test cycle 1, but shows a different behavior for test cycles 2 and 3. The surface temperature relatively quickly reaches a stable value around 28.5 °C in both these tests, indicating that a fully steady state behavior is achieved. The indoor surface temperatures drop quickly after switching off the solar radiation and stabilize at a constant value of approx. 23 °C.

The difference in the temperature of the window surface before the solar radiance is applied and soon after it comes to an end is a measure of the energy stored within the glazing system (and in the PCM layer especially). This temperature difference reaches more than 4°C when the PCM completes the phase change (Test 3, upper part), and up to a bit less than 2°C when the solid-to-liquid transition is not fully exploited.

Figure 3 shows the measured surface temperatures of the two windows with an impinging solar radiation of 500 W/m^2. The surface temperature for the PCM-window in test 4, 5 and 6 is similar to that found in tests 1 - 3 respectively. However, the temperature increase is slower and follows a less steep curve, and the reference window surface temperature stabilizes at 25 C. This is as expected due to the lower impinging solar radiation level and consequently lower energy absorbed by the glazing. A linearizing of the temperature increase development, similar to that in test 3, was found near the end of test cycle 6, indicating that phase transition has been reached also here.

Figure 4 shows results from tests 7-9, which give more information about the combined effect of the thermal gradient and solar irradiation. Thermal energy stored in the PCM glazing systems is reduced if compared to the previous cases (Tests 1-3), due to the fact that the glazing systems have higher heat loss towards the outdoor chamber. Under these circumstances, the maximum temperature difference of the window surface before and after the solar pulses is lower than 3°C (Test 9). When comparing the PCM-window to the reference glazing, it becomes obvious that the thermal inertia of the PCM-window is notable and substantial. Even though the measured surface temperatures of the reference window are always lower than the PCM window the energy storage of the PCM-layer can be qualitatively assessed and expressed by the difference in surface temperatures between the two samples.

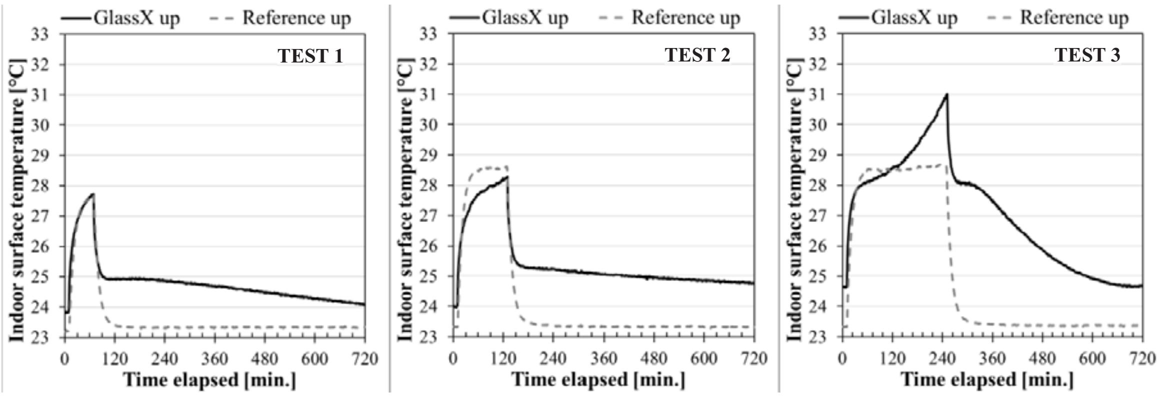

Fig. 2. Surface temperature plots (upper thermocouple) for GlassX sample and reference, for test series 1-3 (TEST 1, left; TEST 2 middle; TEST 3 right). Solar irradiation level 1000 W/m^2; interior and exterior temperature 24 °C.

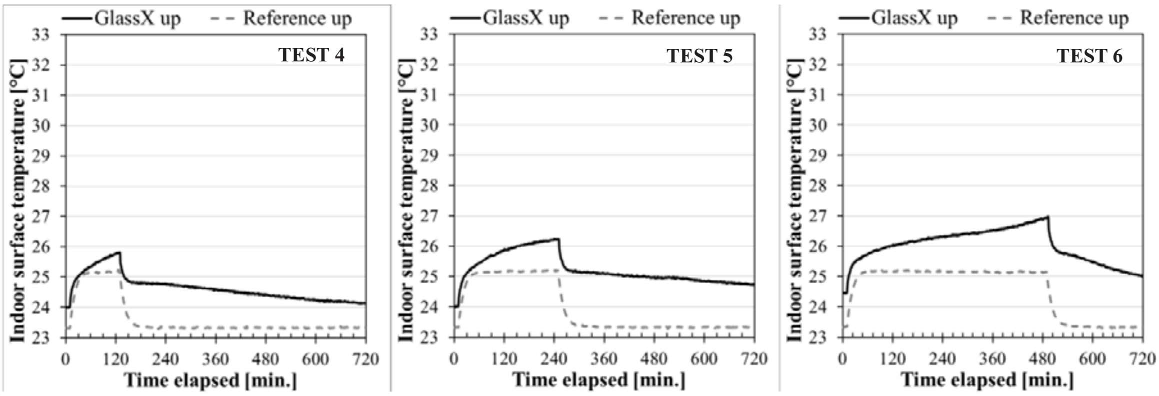

Fig. 3. Surface temperature plots (upper thermocouple) for GlassX sample and reference, for test series 4-6 (TEST 4, left; TEST 5, middle; TEST 6, right). Solar radiation level 500 W/m^2; interior and exterior temperature 24 °C.

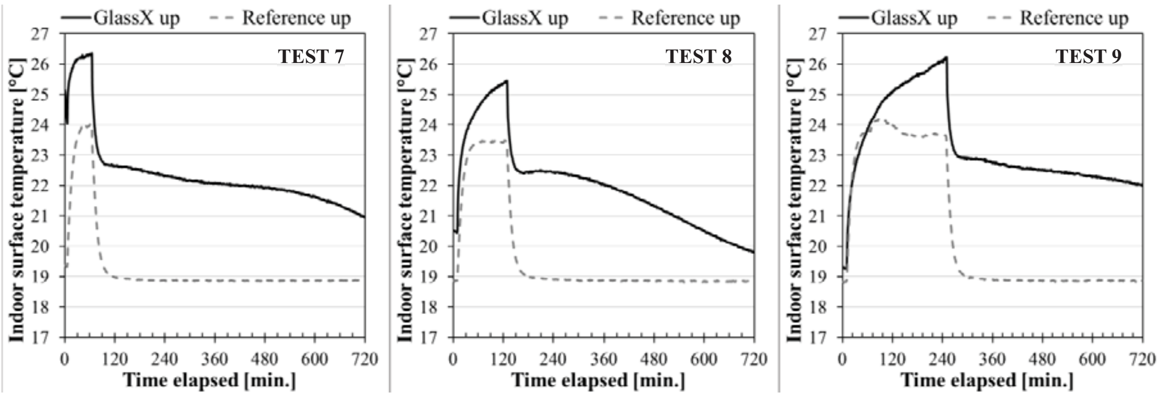

Fig. 4. Surface temperature plots (upper thermocouple) for GlassX sample and reference, for test series 7-9 (TEST 7, left; TEST 8, middle; TEST 9, right). Solar radiation level 1000 W/m2. Interior temperature 24 °C and exterior temperature 10 °C.

The systematic temperature difference between PCM- and reference window can be explained by the much higher *U-value* of the reference window and, to a lower extend, by slightly different boundary conditions at the beginning of the tests. Where the temperature-drop of the reference window is immediate, the drop in the PCM-window is slower and the integrated area in-between the two temperature curves is related to the stored energy.

Furthermore, it is worth highlighting that steady state, once the radiation pulse is over, is not reached in the PCM-window during the eight hour relaxation time before the following radiation pulse. This is another, indirect, quantification of the elevated thermal inertia of the system.

The measurements presented in this paper allow some important consideration for future experimental campaign to be drawn. The very high thermal inertia of the system prevents it to reach a steady state condition if only eight hours are left between two solar stimuli – this phenomenon is especially enhanced when solar stress and thermal gradient stress are coupled, In future analysis, longer relaxation periods need thus to be employed – at least 24 h.

As previously mentioned, a limitation in the study is given by the solar simulator structure. It is not possible to replicate the full optical characteristics of the solar irradiance (i.e. direct and indirect irradiance) with the current test rig. Due to the particular technology under investigation, which employed a prismatic glass, and thus show high dependence on the geometry of the solar radiation, the investigations that can be carried out by means of the measurement facility are somewhat limited.

5. Conclusions

Measurements have been performed on a four-pane window system incorporating a solar reflector and a macro encapsulated PCM layer. Static conditions coupled with pulses of solar irradiation have been studied. A two-pane IGU has also been tested for the sake of comparison with measurements on a well-known technology.

The comparison between the measurements of the surface temperatures of the two glazing systems indicates that the thermal energy storage potential and thermal inertia of the PCM-window is substantial. Higher interior surface temperatures were reached and maintained over a long period of time. This can, in addition to energy saving potentials, also influence and improve the thermal comfort in a room.

For systems with high thermal inertia, like the PCM-based system tested here, the time interval between periodic cycling of stresses must be ensured. Measurements showed that a period of 10-12 hours between two applications of solar irradiation pulses was not enough to completely stabilize the temperatures and to reach steady state conditions.

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