Possibilities for characterization of a PCM window system using large scale measurements

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Abstract

The introduction of dynamic envelope components and systems can have a significant reduction effect on heating and cooling demands. In addition, it can contribute to reduce the energy demand for artificial lighting by better utilization of daylight.

One of these promising technologies is Phase Change Materials (PCM). Here, the latent heat storage potential of the transition between solid and liquid state of a material is exploited to increase the thermal mass of the component. 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.

Measurements have been performed on a state-of-the-art, commercially available 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 PCM, contained in transparent plastic containers.

When dynamic components are incorporated in the building envelope, it makes the characterization of static performance (e.g. the thermal transmittance, U-value; the solar heat gain coefficient) insufficient in giving the full picture regarding the performance of the component in question.

This article presents a series of preliminary measurements, and the related methodologies, carried out on a window with incorporated PCM. The tests have been carried out using several test cycles comprised of temperature and solar radiation cycling, where the aim has been to delve deeper into the possibilities for the characterization of dynamic building envelope components by full scale testing in a climate simulator, showing potentials and limitations of this approach and measurement facility.

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. Long periods of sun combined with high exterior temperatures are needed.

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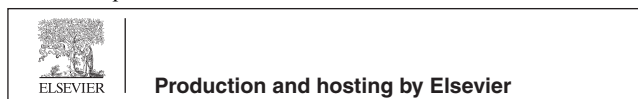
1. Introduction

1.1. Technology overview

Based on the recommendations given in IEA ECBCS Annex 44 and the "Kyoto Pyramid" (IEA, 2011), combined with the fact that windows contribute to a substantial part of

the heat losses and gains, a further investigation on the possibilities of reducing the energy demand related to glazed and/or translucent parts of the facades is necessary.

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 raw materials used to produce PCM's can be divided in three main groups, eutectic, organic and in-organic materials (Baetens et al., 2010). For the use of PCM in windows, paraffin based, organic materials are the most interesting, since they are transparent in the liquid state and translucent in the solid state.

Some studies concerning PCM in combination with glazing have previously been performed. These range back to 1997, with a study of the PCM layer coupled with a transparent insulated material (Manz et al., 1997). 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 behavior is achieved thanks to the highly selective optical properties of some PCM, e.g. paraffin wax. An investigation of the optical properties of PCM layers in combination with glazed layers was carried out, by means of a Large Integrating Sphere facility, by Goia et al. (2012), who characterized different thicknesses of the PCM and the angular-dependence of the coefficients.

The use of PCM as moveable shutters was studied by Ismail and Henriquez (2001). Here, PCM are pumped to and from a storage tank underneath the window. The authors conclude that a PCM filled window is thermally more effective than an air-filled window as it filters out thermal radiation which in term reduces heat gains or losses. Weinläder et al. (2005) performed measurements on a double glazing with a PCM acting as a third (internal) layer to the glazing unit. The authors found that a reduced heat loss compared to the double-glazing unit is mainly due to the additional cavity behind the PCM. There was also found a slight shift in peak energy flows when using the PCM, but the authors concluded that if the heat gains of a double glazing (higher during mid-day) can be stored it might overcompensate the high heat losses of this system. However, the addition of PCM has a positive effect on thermal comfort by dampening the extreme temperatures during mid-day and night.

A study where PCM was used for latent heat storage in an internal slat-blind shading device (Weinlaeder et al., 2011), concludes that there is a substantial cooling potential during summer, and also some benefits during wintertime, compared to a conventional material blind. Whereas, the PCM used here are not transparent, it is used in combination with a window, thus making it part of a transparent component. Likewise, a numerical simulation study for externally placed shutters with PCM (Alawadhi, 2012), conclude that the heat gain through the window can be significantly reduced when mounting shutters with PCM compared to an un-shaded window. A comparison of two-pane windows with a gas-filled cavity and a PCM filled cavity was performed by Ismail et al. (2008). Goia et al. performed an experimental analysis on a double glazing system with paraffin wax, by means of an outdoor test cell facility located in a temperate sub-continental climate (2010). Implications of this system on thermal comfort condition were also investigated starting from experimental data (Goia et al., 2013), and physical–mathematical models (Goia et al. 2012) for simulating PCM glazing systems were developed too. Recently, Gowreesunker et al. (2013) analyzed the optical and thermal properties of a small scale PCM-glazed unit, assessing its performance by a combined experimental–numerical analysis. The investigation focused on the relationships that describe the extinction, scattering and absorption coefficients within the phase change region, validated in a numerical CFD model.

1.2. Scope of work and possible outcome

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 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 Cao et al. (2010). The measurements carried out for an opaque wall incorporating PCM presented in this article have been used for validation of a numerical model (Tabares-Velasco et al., 2012). 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.

1.3. The PCM glazing

Measurements have been carried out on a commercially available glazing system with an integrated prismatic solar reflector and a PCM filled cavity. 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. The PCM glazing is often combined with standard windows in the façade, as shown in Fig. 1. The window is a 1.2 by 1.2 m large window which consists of a four-pane

glazing package A solar reflection device, i.e. a prismatic glass (Christoffers, 1996) is placed in the outermost cavity, the second is argon-filled cavity, and the innermost, third cavity is filled with a polycarbonate encapsulated PCM. A cross-section of the window is shown in Fig. 2. The window optical and thermal properties are shown in Table 1.

2. Test method and measuring equipment

2.1. The climate simulator

In this work, measurements have been performed on a state-of-the-art glazing system incorporating PCM using a climate simulator. The climate simulator is an apparatus in which the climatic conditions on both sides of a building component sample can be dynamically controlled.

The climate simulator is made up of two chambers, separated by the sample. The left side, as shown in Fig. 3, is used to simulate exterior conditions. In this chamber, the temperature can be controlled from −20 to +80 °C. Relative humidity levels can be varied between 20% and 95%. In addition, both water (rain) and solar radiation can be applied. The solar radiation is supplied with nine xenon lamps. The lamps have been calibrated in order to produce a maximum, nominal solar radiation level of 1 kW/m^2 integrated over the full spectrum, evenly distributed over the

Fig. 1. On the left; External view of building with a combination of standard windows and PCM-windows (Architekten, 2000a). On the right; internal view of standard windows and PCM-windows in combination, PCM being the semi-translucent elements on the sides of the windows (Architekten, 2000b, 2004.
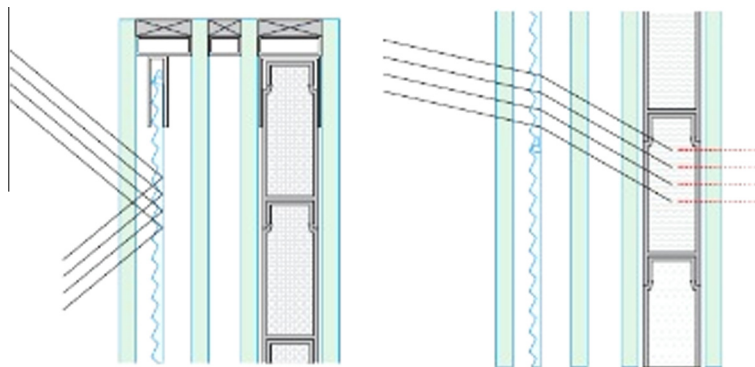

Fig. 2. Vertical cross sections of the PCM window. (GlassX, 2012). The figures illustrate the angular properties of the solar reflector in the outer cavity, where radiation with high incidence angles (typical summer days) are reflected and low-angle incident radiation (typical winter days) is let through.

Table 1
Declared and measured thermal and optical values of the PCM glazing.(GlassX, 2012; Salvesen et al., 2012). The value of α in the measured values in columns, show the angle of incident light.

	Declared values (GlassX, 2012)			Measured visual transmittance values (Salvesen et al., 2012)		
	U-value (W/m^{2}K)	Solar heat gain coefficient (g-value)	Visual transmittance (Tvis)	Direct – diffuse $\alpha = 0$	Direct – diffuse $\alpha = 30$	Diffuse – diffuse
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%)			

entire sample area and with a wave-length distribution similar to that of the sun. The lamp array is placed with a perpendicular distance to the test sample of 1 m. All lamps can be switched on and off individually and the effect can be varied step-less down to 50% of the maximum level. The lamps produce a homogenous irradiance level over the entire sample, thus making studies of angular properties more difficult. The other, right, side on Photo 2 represents the interior side of the construction. Here, the temperature can be varied within a range of +5 to +50 °C. Relative humidity levels can be varied between 20% and 95%. The air temperatures in both adjacent test chambers are based on temperatures measured in the exhaust air from their respective chamber, and are thus representative of the average air temperature inside each thermostatic chamber. Concerns may rise as far as the air temperature in front of the lamps array, since the xenon lamps may warm up the air layer that borders with the solar simulator. It is important to stress that the exact measurement of the temperature in the air gap between the lamps array and the sample can be difficultly assessed, since thermal sensor readings may be deeply influenced by the short-wave radiant flux, and thus result in inaccurate measured values. The air gap overheating phenomenon is reduced to the minimum extent by the following measures: the lamps array is placed far enough from the sample (1 m) in order to have a significant air layer between the lamps and the sample; the air-change rate in the chamber that hosts the solar simulator was kept at a high level in order to ensure sufficient ventilation in the gap between the lamps and the sample.

2.2. Instrumentation

Heat flows, temperatures and solar radiation levels were continuously monitored and logged during the experiment. Temperatures were measured using type T thermocouples in five positions on each side of the test specimen. The T-type thermocouples have a declared uncertainty of ±2%. Heat fluxes were measured using four heat flow

Fig. 3. The climate simulator used for the PCM-glazing measurements.

meters (HFM), whose nominal measurement error provided by the producer is ±5%. Solar radiation levels, both on the "outdoor-side" of the sample (impinging solar flux) and on the "indoor-side" of the sample (transmitted solar flux) were measured on the vertical plane, in the 300–3000 nm spectral range using two pyranometers. The nominal accuracy of this sensor is ±5%. The solar radiation levels were measured using a pyranometer placed on the lower right (seen from the exterior side) side of the specimen 10 cm from the surface, see Photo 3. On the interior side, an identical pyranometer was placed in the center axis of the test specimen approximately 1 m from the interior surface so that no direct shading from HFM or other sensors affected the pyranometer.

Due to different absorptivity, emissivity and surface properties of the thermocouples and HFM compared to the glazing unit, shielding from direct solar radiation was found to be necessary in order to reduce the influence of the short-wave radiant flux on the sensor readings. A rigid, reflective aluminum foil was placed as a radiation shield over the sensors leaving a 2 cm wide ventilated cavity between the foil and the sensor, as shown in Fig. 4. This was done to avoid overheating of the sensors due to direct radiation. A similar procedure with shielding of sensors has previously been applied with success in previous studies (Corgnati et al., 2007; Zanghirella et al. 2007; Goia et al., 2010).

2.3. 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 knowledge of the thermophysical and optical behavior of such systems. This can later be used to plan a more dynamic measurement campaign. Table 2 shows the overview of all test cycles performed. The table describes the interior- and exterior temperature, the average level of solar irradiance across the sample and the duration of each test cycle. The tests were run with solar irradiance levels and durations as stated in Table 2. Between each test cycle the solar irradiance level was set to zero for a set period.

In the experiments carried out in this work, the main focus is placed on the influence of solar irradiance on the PCM layer, combining different short-wave radiation fluxes with different thermal gradients and temperature levels. In particular, Test 1–6 exclude the effect of heat transmission due to thermal gradient between the outdoor and the indoor chamber, and allow deep analysis to be done on the influence of solar irradiance alone. On the contrary, Test 7–9 present a thermal gradient (10 °C) between the two chambers and short-wave radiation pulses, giving pictures of combined mechanisms due to different stresses.
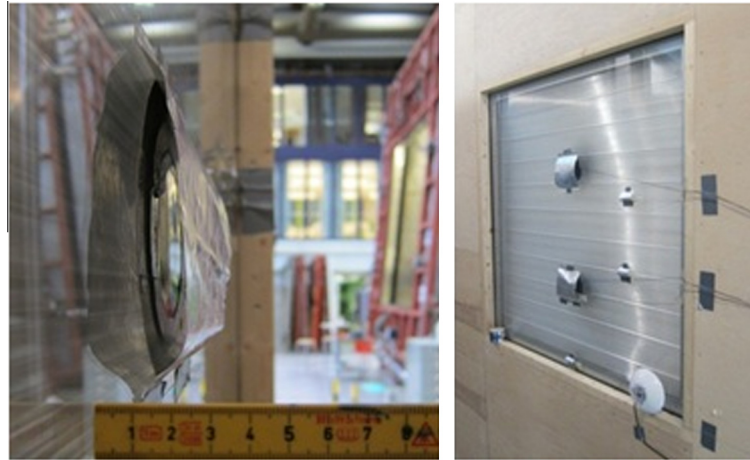
Fig. 4. The picture on the left shows details of the radiation shielding of HFM's using a rigid, reflective aluminum foil. The picture on the right gives an overview of the instrumentation of the PCM window, showing thermocouples and HFM's shielded with aluminum foil placed at two levels (up and down). The pyranometer is visible in the lower right corner of the PCM window.

Table 2
Test cycle descriptions.

Test #	Indoor air temperature (°C)	Outdoor air temperature (°C)	Solar irradiance/ duration	Aim of study
1	24	24	1000 W/m^2/1 h	Study the influence of the solar radiation in a temperature range close to the
2	24	24	1000 W/m^2/2 h	transition phase; no contribution of thermal gradient between outdoors and
3	24	24	1000 W/m^2/4 h	indoors; conditions similar to summer period (with no temperature swing)
4	24	24	500 W/m^2/2 h	Study the influence of the solar radiation in a temperature range close to the
5	24	24	500 W/m^2/4 h	transition phase; analysis of the influence of the density of solar irradiance (500 vs.
6	24	24	500 W/m^2/8 h	1000 W/m2) on the behavior of the PCM layer (same irradiation of test 1–3)
7	20	10[*]	1000 W/m^2/2 h	Study the influence of the solar radiation in a temperature range far from the
8	20	10[*]	1000 W/m^2/4 h	transition phase; contribution of the thermal gradient between outdoors and
9	20	10[*]	1000 W/m^2/8 h	indoors; conditions similar to a winter situation

3. Results

3.1. General discussion

As already mentioned, the introduction of dynamic properties in façade components makes characterizing them a complex task. Traditional static parameters, like the thermal transmittance (*U*-value) and solar heat gain coefficient, are unable to fully describe the thermal performance and their significance becomes questionable too.

The measurements performed points out some of the potential benefits of dynamic systems like this. It also shed light on some of the challenges encountered in the measurement procedure.

3.2. Solar irradiance and transmittance measurements

Measurements to assess the direct solar transmittance level of the system have been carried out. Table 3 shows the irradiance levels on the exterior- and interior side of the climate simulator as well as the solar transmittance of the PCM-window. An example graph of the measured irradiance levels is shown in Fig. 5. Table 3 shows fairly consistent results for the irradiance level differences

between the exterior and interior, which is in principle what the solar transmittance shown here is. A slightly lower value is recorded when an outdoor solar irradiance of 500 W/m^2 was employed (tests 4–7). When 500 W/m^2 was employed the power of the lamps was reduced to 50% of max nominal power. The reduction of output level leads to a small change in the solar spectrum of the lamps. This is likely the cause for the reduced measured solar transmission values for the series with 500 W/m^2. The measured value of the GlassX window is sensibly lower than that measured in previous experiments, and this can be explained considering the more complex layer structure of the specimen under test – that includes a prismatic glass, polycarbonate containers and a much thicker PCM layer.

There seems to be no relevant difference in the direct solar transmittance between the solid state and the liquid state (which is reached, at least partially, in Test 3). This behavior can also be explained considering the complex structure of the glazing, where the optical properties of the PCM layer alone have a much lower impact on the total behavior than other, simpler configuration investigated in the literature (Goia et al. 2012; Gowreesunker et al., 2013).

Table 3
Solar irradiance levels on interior and exterior sides (W/m²K) of the sample and the interior irradiance level relative to the exterior irradiance level.

Test cycle nr	Exterior irradiance (W/m²)	Interior irradiance (W/m²)	Solar transmittance (−)
1	1115	149	0.13
2	1225	154	0.13
3	1241	164	0.13
4	478	53	0.11
5	488	54	0.11
6	486	56	0.11
7	1285	197	0.15
8	1236	174	0.14
9	1156	161	0.14

3.3. Surface temperature measurements

The measurements performed in test series 1–3, were carried out with the highest solar radiation level of all the series. For the first two cycles, as shown in Fig. 6, it is possible to see that the temperature propagation for both the interior and exterior measuring points follow a smooth exponential development, thus indicating that the phase change dynamics of the glazing have been activated. However, for the third cycle where the duration of the solar stress was four hours, it is possible to verify that the tem-

perature increase of the interior surface has a larger gradient for the latter part of the period. This, more linear temperature propagation indicates that the phase transition temperature of the PCM has been reached and the internal temperature of the PCM will increase undisturbed by the latent energy storage effects of the phase transition. When the lamps are turned off and solar stress comes to an end, it can be observed that the instant temperature drop is fast, but that 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. Furthermore, it can be derived from Fig. 3 that the upper and lower thermocouple shows different values. This can be explained considering the temperature stratification within the specimen itself, that is a quite common feature in glazing systems that contains cavities filled with air or other gases (Manz, 2003). It is also possible to relate this phenomenon to an air-temperature stratification in the gap between the sample and the solar simulator, although it has been already discussed that, because of the structure of the facility measurement, this aspect is (very likely) reduced to the minimum extent – but cannot be completely ruled out. The temperature stratification is so relevant that, in Test 3, the PCM contained in the upper part of the window completes the phase transition and is in liquid state when the solar simulator is turned off, while that contained in the lower part of the window is still in the transition phase. It is worth mentioning that the stratification phenomenon seems to be enhanced when a higher solar flux impinges on the window (Tests 1–3 and 7–9), with a temperature difference along the height of the window of more than 2 °C.

From Figs. 7 and 8 it is possible to observe that the highest interior temperatures reached are approximately
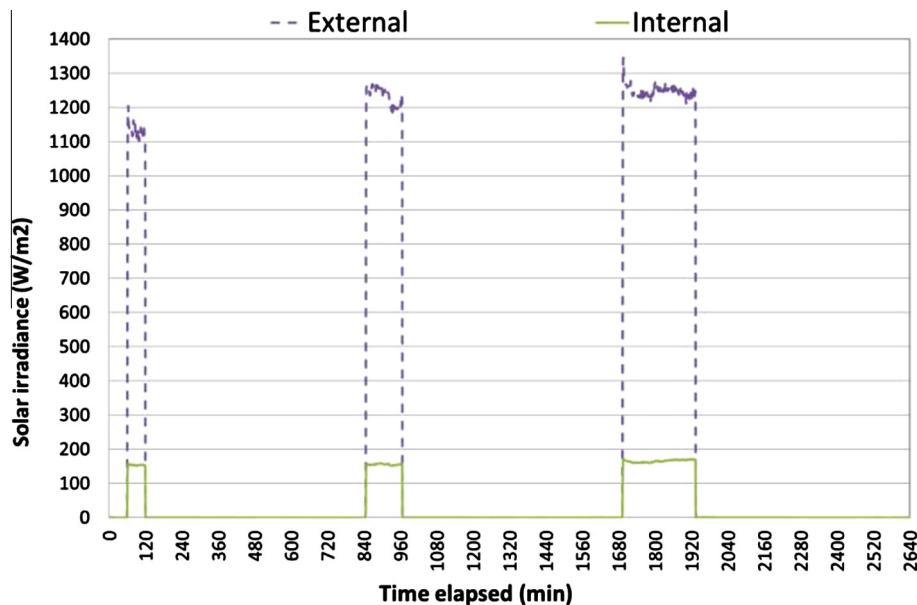

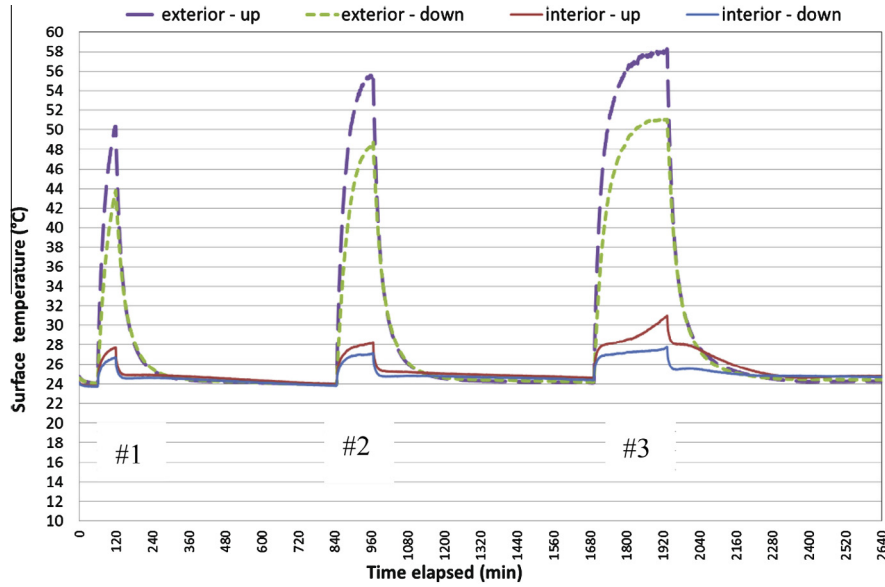Fig. 5. Solar irradiance level measurements for test cycles 1–3.

Fig. 6. Surface temperature plots for test series 1–3. Solar radiation level 1000 W/m² and interior and exterior temperature 24 °C.

26–27 °C. The temperature development follows an exponential curve for all the measurements and it is clear that the temperature range for phase change of the PCM is reached.

The difference in the temperature of the window surface before the solar stimulus 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.

Tests 7–9 give more information about the combined effect of thermal gradient and solar irradiation. It is possible to see that the thermal energy stored in the glazing

systems is reduced compared to a reference situation (Tests 1–3), where there is no heat loss toward the outdoor chamber – under these circumstance, the maximum temperature difference in the window surface before and after the solar pulses is lower than 3 °C (Test 9). Furthermore, one can see that steady state of the system is not reached during the eight hour relaxation time between solar exposures for the measurements in Fig. 5. This is an indirect measurement of the elevated thermal inertia of the system.

4. Discussion and future work

The preliminary measurements presented in this paper allow some important consideration for future experimental campaign to be drawn.
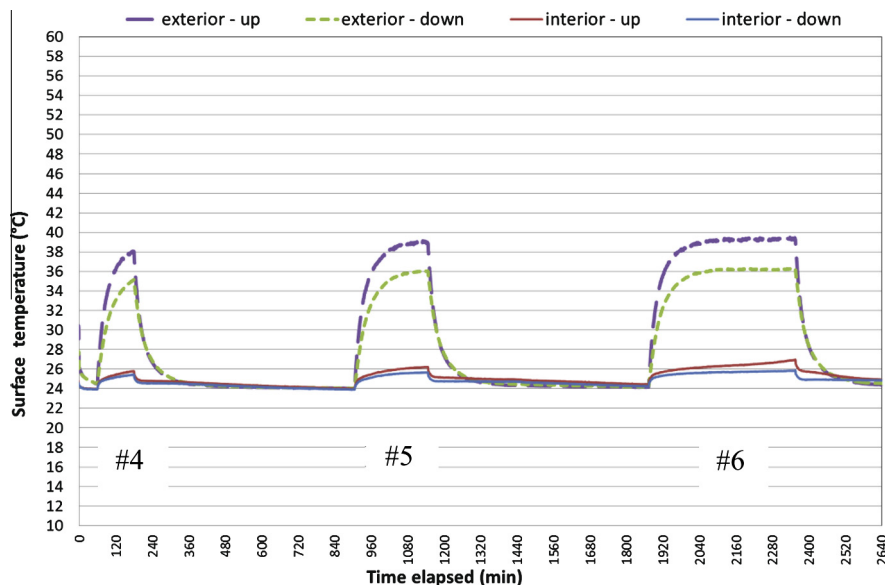

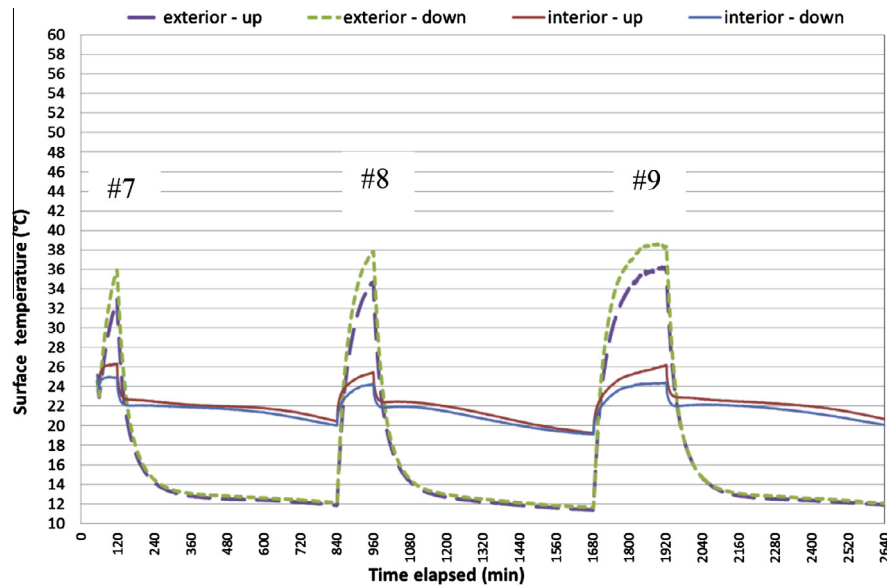Fig. 7. Surface temperature plots for test series 4–6. Solar radiation level 500 W/m². Interior and exterior temperature 24 °C.

Fig. 8. Surface temperature plots for test series 7–9. Solar radiation level 1000 W/m². Interior temperature 24 °C and exterior temperature 10 °C.

The temperature stratification on the window is more significant than expected, and probably to be related to the highly non-linear behavior of the PCM layer – the stratification is enhanced by the fact that in some areas the PCM completes the melting process, while in other it stays in a solid–liquid mixture during the whole test. This makes it necessary to measure the surface temperature in several places in order to have a full picture of the window thermal behavior.

The very high thermal inertia of the system prevents it reaching a steady state condition if only 12 h 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.

The window were instrumented with two heat flow meters (HFM) on each side of the glazing unit with the goal of measuring the thermal transmittance of the glazing unit. These measurements were performed in separate test series for both liquid and solid state of the PCM. No solar radiation was applied in these series. The measurements were, however, not reliable and gave large variations. After the test had been performed, it was discovered that the lower HFM on the exterior side of the sample had detached from the window surface and that the upper exterior HFM had curved, thus creating a air cavity between the sample and the HFM. This was probably caused by thermal stresses to the HFM. In addition, the opposing HFM's placed internally and externally showed incoherent values. Hence, proper thermal transmittance measurements using a hot box or similar should be performed in order to get reliable results.

A limitation in the study is given by the solar simulator structure. It is not able to replicate the full optical characteristics of the solar irradiance (i.e. direct component plus indirect irradiance). Due to the particular technology under investigation, that includes a prismatic glass, and thus has a high dependence on the geometry of the solar radiation, the investigations that can be carried out by means of this measurement facility are partial. Unfortunately, it is not possible to solve this issue with the available test rig. In order to overcome this limitation, a measurement campaign using an outdoor test cell facility is planned.

Furthermore, the measurements presented in this article are presently limited to steady state conditions. They should be expanded with test cycles imitating real climate data and for a better understanding of the behavior. Conventional systems (e.g. a triple glazed unit) will be measured using the same cycles for ease of comparison. Finally, more reliable U-value measurements will also be carried out.

5. Conclusions

Measurements have been performed on a four-pane window system incorporating a solar reflector in the outermost cavity and a PCM layer in the innermost cavity. Both static parameters as well as characterization of the dynamic response of the system have been studied.

Solar irradiance levels were measured on the interior and exterior sides of the sample, yielding consistent numbers for the amount of radiation transmitted through the sample, regardless the state of aggregation of the PCM. This value gives one of the components of the SHGC for the system. The value does not, however, take into account the factors of heat transport due to other transfer mechanisms induced by the effect the solar radiation has on the surface temperatures and gradients over the sample cross-section. These heat transfer effects will be the subject of future studies. 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. Long periods of sun combined with high exterior temperatures are needed. This suggests that lower melting point temperatures for the PCM could be considered for cold climates in order for a better utilization of the latent heat storage potential.

For systems with high thermal inertia, like the PCM-based system tested here, sufficient time interval between periodic cycling of stresses must be ensured. Measurements showed that a period of, in this case, 10–12 h between applications of solar radiation was not enough to ensure the complete stabilization of temperatures and steady state conditions between the stress cycles.

Acknowledgements

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