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Phase Change Materials in glazing: implications on light distribution and visual comfort. Preliminary results

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Abstract

The visual comfort concerned with a technology with PCM embedded into a double glazing unit was analyzed, using the Daylight Probability Glare and the 'Useful Illuminance' (percent of workplane with an illuminance in the range 100-3000 lx). A sample office room was modeled using Radiance, under a clear sky and with the façade facing south.
The visible transmittance of PCM was measured in laboratory and used as input in Radiance. The simulations were carried out for the two solstices and the Autumn equinox (four hours per day), for three sites (Östersund, 63.2°N; Turin, 45.2°N; Abu Dhabi, 24.4°N), considering the solid state of the PCM only.

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Keywords: phase change material (PCM); visual comfort; glare; Radiance simulation; Daylight Glare Probability; Useful Illuminance.

1. Introduction

During the last decade, the research activity in the field of building envelope components and building services has led to the identification and implementation of numerous solutions able to considerably reduce the energy need in buildings. Relevant improvements can be achieved by conceiving envelope components as "living" membranes [1]. With such an approach, the building envelope is actively used to filter, store and/or modify the mass and heat flux between the indoor and the outdoor, with the aim of assuring an optimal Indoor Environmental Quality with minimum energy demand [2]. A key feature is thus the capability of the building envelope to react and change its properties and features over time. Adaptiveness of transparent façades can be achieved through different solutions

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and materials (e.g. an air flow in a cavity [3-4], integration of Phase Change Materials (PCM) [5], switchable layers [6]), and can perform at different timescales and take place at different component/system levels. Therefore, these façades are particularly complex to be characterized, due to the high level of dynamicity and to the interdependency among different performance aspects. The lack of synthetic metrics and standardized characterization procedures are also major barriers that prevent the diffusion of this kind of concept/technologies.

When the focus is limited to the influence of an adaptive transparent façade on the visual comfort in the indoor space, the selection of performance criteria is often not so straightforward [7,8]. The standardized visual comfort condition [9] depends on the relationship between the user needs and the luminous environment. This is usually assessed by evaluating the amount, quality and spatial distribution uniformity of light, together with the estimation of the risk of glare (both disability glare and discomfort glare) for the user. For this analysis, the use of daylight metrics that incorporate temporal and spatial considerations is necessary to fully address the human perception of a space. The integration of space and time variable in one metric is clearly a challenge in case of conventional glazing systems, and becomes even more problematical for glazing components that exhibit dynamic optical properties. To analyse the glare risk, complexity is further increased by spatial (user position and luminance distribution) and physiological (subjective adaptation to luminous environment) variables. For office buildings, the Daylight Glare Probability (DGP) [10] is the most-widely accepted metric to assess the discomfort glare risk for side-daylighting conditions. This index is based on empirical correlations between the luminance distribution in the visual field (taken into account through the vertical illuminance measured at the eye level) and the glare perceived by the users.

Visual comfort implications and glare risk were investigated for dynamic fenestrations equipped with shading systems [11], or switchable glass panes [12], as well as for (static) translucent façades [13]. This latter investigation also points out that glare risk may be noticeable when a translucent façade (with a total light transmittance of 29%) is adopted and that it was not possible to prove the hypothesis that the glare sensation may be reduced if a part of a façade enables a view to the outside, due to psychological aspects [14,15].

Results from investigations on visual comfort condition and glare perception for translucent windows are a relevant benchmark when assessing the implication on the visual environment of a given dynamic glazing technology, based on the incorporation of PCM. While extensive experimental and numerical analyses of the performance of PCM glazing systems have been conducted and results are available in literature [5], no information can be currently found on the performance of this/these concept/technologies on the visual environment of a room equipped with this glazing system. Several PCMs that are adopted in these glazing solutions are in fact partially transparent to electromagnetic radiation (translucent to visible light when in solid and in transition phase state, and transparent when in full liquid state). While the liquid state is characterized by an optical behavior very similar to that of a conventional glazing system, the solid state is characterized by dominant scattering phenomena, that make the evaluation of the performance of this system much less trivial than for conventional windows.

The idea of integrating PCM into glazing components arose with the aim of improving both the thermal inertia and the overall performance of the glazed components, by allowing a better exploitation of solar energy. Most of the visible radiation is transmitted by PCM glazing system and this allowed daylight to be exploited, while most of the infrared radiation was absorbed and converted into heat. Different configurations of this main concept have been tested or simulated along the time, ranging from simple systems (e.g. a double glazed-unit where the cavity is filled with a PCM [16-20], to more advanced solutions that make use of triple-glazed units [21,22] equipped with dynamic glass panes [23], prismatic glass panes [24-26], or additional insulation materials [27].

Within this frame, this paper presents the preliminary results from a research activity on the impact of a PCM transparent façade on the visual comfort for the occupants, in a typical office room. As a first stage of the study, some extreme conditions, such as a totally transparent façade and a direction of view perpendicular to the window, were assumed, so as to define a worst-case scenario to characterize the performance of the component. Furthermore, the PCM was investigated in its solid/transition state only, because of two reasons. Firstly, the liquid state presents a conventional, specular behavior, with a visible transmittance in the same range of that of a conventional double glazed unit; therefore, the impact on the visual comfort can be then easily derived from well-established knowledge about conventional glazing systems. Secondly, the optical and thermal performance of a PCM layer in liquid state is, globally, worse than for the solid/transition state; a well-designed PCM glazing system should remain in solid (or better, transition) phase for most of the time, and never reach the (full) liquid state. Furthermore, the analysis was preliminarily limited to one orientation only for the transparent façade, to the presence of clear skies only and to a limited number of time-step during the course of a year, so as to highlight potential problems concerned with PCM.

A simple configuration, consisting of a double glazed unit with the cavity filled with a paraffin wax, was used in the study, so as to make conclusions more general and independent of additional technologies (such as shading systems or other insulation layers). This configuration was previously analyzed experimentally in a test cell facility (thermophysical and energy performance [17]; thermal comfort [16]) and in laboratory (optical properties [28,29]).

The paper presents a numerical analysis based on the lighting simulation tool Radiance. Experimental values of the visible transmittance of the a Double Glazed Unit (DGU) measured during the laboratory characterization [29] were implemented in the Radiance model and a set of simulations were carried out for some days during a year. This investigation is also meant to be a case-study to develop a new method for numerical simulations, numerical data post-processing and communication of performance metrics in the field of visual comfort. A new metric, the '*useful illuminance*', i.e. the portion of workplane with illuminance values in a comfort range, is proposed too.

2. Method

2.1. Glazing systems

The PCM glazing component is based on a DGU. It consists of two 4 mm extra-clear glass panes and a 15 mm commercial grade paraffin wax layer between the two glass panes. It was characterized according to experimental data obtained from laboratory measurements by means of an Ulbricht sphere with large diameter (75 cm) and a spectrophotometer [29]. Although the PCM is well known for its phase changing properties, the aim of this study is to investigate its lighting performance when in solid state, as the optical behavior when in liquid state is very similar to that of a specular glass. The outcomes of the previous experience showed that in its solid state the PCM is a translucent material with a nearly Lambertian behavior. The measured visible transmittance, reflectance and absorptance were found to be as follows: T_v=55%, R_v=33% and A_v=12%, respectively. When in transition phase, the behavior is still nearly Lambertian: it is enough just a very thin layer of solid PCM to determine a high scattering effect, which results in a predominance of transmitted radiation with diffuse mode.

The reference case was chosen to allow the transmission properties of the PCM component and of a specular glass with the same light transmittance to be compared. As a result, a selective glass with a T_v of 50% was adopted.

2.2. Case study and numerical modelling

The sample room is a single office, 3.6 m in width, 5 m in depth 2.7 m in height (Figure 1). One of the two 3.6x2.7 m walls contains a window, which covers its whole surface, with a resulting window-to-wall ratio of 1. The window is subdivided into three sections both vertically (each section with a width of 1.2 m) and horizontally. The lower and upper sections are 0.75 m high, while middle section is 1.2 m high. This layout was adopted to comply with the window frames currently offered on the market and adopted in many office buildings.

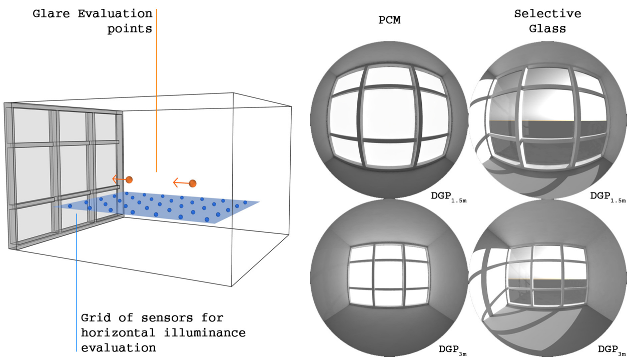

Fig. 1. Left: 3D representation of the sample office model showing the grid of sensors to calculate the E values [blue] and the DGP [orange]. Right: example of images to calculate $DGP_{1.5m}$ and DGP_{3m} for the PCM and selective glass.

The room was assumed with the façade facing south under a clear sky with sun. The two technologies were tested for different geographical and time conditions, with the purpose of evaluating the influence of different boundary conditions on the transmission properties and hence on the luminous environment in the sample room. Three locations were chosen: Östersund, Sweden (latitude L=63.2°N, longitude l=14.5°E), Turin, Italy (L=45.2°N, l=7.65°E), and Abu Dhabi, United Arab Emirates (L=24.4°N, l=54.65°E). The simulations were run for three different moments of the year: the summer solstice (June 21st), the autumn equinox (September 21st) and the winter solstice (December 21st). These represent the limit cases in terms of solar elevation and irradiance (winter and summer solstices), as well as an intermediate situation (autumn equinox). For each day, four different simulations were run for the following hours: 9:00, 12:00 (noon), 15:00, and 18:00. A total amount of 72 different cases were obtained and simulated to consider all the combinations between the variables, using the validated lighting software Radiance (simulation parameters used as input: ab=5, ad=1024, as=256, ar=256, aa=0.05). The following Rhinoceros parametric tools were exploited to manage the simulation procedure: Grasshopper, used to model the sample office, and two of its own add-ons, Ladybug and Honeybee, used to manage the Radiance compatible materials and run the simulations. These add-ons offered two main advantages: on the one hand, they allow Radiance to be used to perform the computation; on the other hand, they allowed the research team to manage the simulations in a parametric way, running a great number of analyses in sequence and organizing the results according to specific, user-defined necessities.

The Radiance model was characterized with *plastic* material for all the opaque surfaces; the R_v values were set to 80% for the ceiling, 65% for the walls, 35% for the floor, 75% for the window frame and 15% for the albedo. The PCM component was simulated with a Radiance *trans* material, whose parameters were defined in accordance to the experimental measures of direct and diffuse transmittance/reflectance. The *diffuse* R_v and T_v were set to 32% and to 54%, respectively, while the *specular* R_v and T_v were set to 1%, as the PCM is a nearly perfect Lambertian material. Spectrophotometrical analyses showed that a PCM layer, both when in solid and in liquid state, presents an almost constant transmission and reflection coefficient profile throughout the entire visible spectrum, without any particular selective behavior [28-29]. Finally, the selective glass was modelled through a glass material with a T_v of 50%.

2.3. Data post-processing, data analysis, and performance metrics

The visual comfort conditions inside the room in the presence of the DGU with PCM and of the DGU with selective glazing were assessed through two metrics: the horizontal illuminance over the work plane and the DGP [10]. A combined analysis of these two outcomes, calculated for all the 72 cases, was performed to better describe the visual comfort concerned with the two technologies under the different analysis conditions.

The work plane horizontal illuminance was evaluated over a regular grid of points sized to cover the whole room, positioned 0.75m above the floor, with a regular spacing of 0.5 m between one node and another (for a total of 35 calculation points). The DGP was calculated for two different points in the room, both positioned on the room endwise axis at a distance of 1.5m and 3m from the window, respectively. The points were set at a height of a person seated, i.e. 1.2 m above the floor, with a direction of sight perpendicular to the window surface, so as to consider the most disadvantageous condition in terms of potential glare.

The average horizontal illuminance over the work plane was not considered as a representative metric in terms of visual comfort, as it does not give any information about the spatial distribution of the illuminances. As a consequence, a new metric was specifically defined, that represents the percentage of grid points whose illuminance lies in a comfort range. The lower and upper E threshold values of the comfort range were set to 100 lx and 3000 lx, respectively, in accordance with the limits introduced by Nabil and Mardaljevic [30] for the Useful Daylight Illuminance UDI. Nabil and Mardaljevic named the resulting three UDI ranges as follows: '*fell-short*', a range of E values for which daylight can be considered substantially lacking, thus raising the need for electric lighting; '*achieved*', a range of E values which are considered 'useful'; '*exceeded*', a range of E values that can result overabundant and which are therefore meant to detect the likely appearance of glare.

Following up this approach, the new metric was called 'Useful Illuminance (E_u)' and, consistently with the UDI metric, includes a set of three different indexes: E_{u_100}, E_{u_3000}, $E_{u\_100\text{-}3000}$, which represent the percentage of work plane where E is below 100 lx, over 3000 lx and between 100 and 3000 lx, respectively. The background of the E_u is similar to the UDI, but with a conceptual difference: the UDI gives a temporal information about the occurrence frequency throughout a year of illuminance in a point lying in a certain range, while the E_u gives a spatial information, that is how many points of the grid lie in a given illuminance range. In a visual comfort perspective, the $E_{u\_100\text{-}3000}$ is to be maximized, the E_{u_100} and E_{u_3000} to be minimized.

For glare analyses, the DGP, which expresses the glare probability for a point in a specific direction of observation, was considered as the most reliable indicator and therefore adopted in the analysis. The reference values to interpret the DGP values were introduced in [10]: a value of DGP<35% describes a condition of 'imperceptible glare', a DGP value between 35% and 40% a condition of 'perceptible glare', a value between 40% and 45% a condition of 'disturbing glare' and a value above 45% a condition of 'intolerable glare'.

The E_u value and two DGP values (for the two positions in the room) was calculated for all the 72 cases, thus obtaining a large dataset to analyze. A further step was therefore taken to define ways to process and synthetize the simulation results. In fact, the metrics calculated in the first stage of the analysis describe the visual comfort performance of the two technologies for a specific time-step during the course of a year and of a day. However, the purpose of the study was also to investigate the 'overall' performance of the two technologies, i.e. to describe a temporal average performance throughout the 12 reference time-steps along the year considered in the study. As a result, the number of data to manage in this second stage of the analysis was reduced to a total of 12: the three geographical locations, the two orientations and the two technologies under investigation. In detail, the following metrics were calculated:

- average Useful Illuminance ($E_{u,av\_100\text{-}3000}$), i.e. the mean of all the $E_{u\_100\text{-}3000}$ values calculated for each time-step
- average DGP (DGP_{av}), defined as the mean of the DGP values calculated for each of the 12 time-steps. This metric was calculated for two points in the room ($DGP_{av\_1.5m}$ and DGP_{av_3m}).

As a further step, the temporal average DGP_{av} and $E_{u,av}$ values were subdivided into four synthetic classes (Table 1). These are meant to characterize the visual comfort in the considered rooms in terms of performance classes: the class A actually shows a better performance in terms of both glare control and of useful illuminance $E_{u\_100\text{-}3000}$.

Table 1. Performance classes for both the DGP_{av} and the $E_{u,\,av}$.

DGP_{av} [10]	E_u
Class A: 0 < DGP_{av} < 0.35 ('imperceptible glare')	Class A: 0.75 < $E_{u,av\_100\text{-}3000}$ < 1
Class B: 0.35 < DGP_{av} < 0.40 ('perceptible glare')	Class B: 0.50 < $E_{u,av\_100\text{-}3000}$ < 0.75
Class C: 0.40 < DGP_{av} < 0.45 ('disturbing glare')	Class C: 0.25 < $E_{u,av\_100\text{-}3000}$ < 0.50
Class D: 0.45 < DGP_{av} < 1 ('intolerable glare')	Class D: 0 < $E_{u,av\_100\text{-}3000}$ < 0.25

As for the E_u classes, a classification similar to that adopted in a study from Berardi et al. [31] for the $UDI_{100\text{-}2000}$ metric was adopted. In their study, Berardi et al. classified the daylighting condition in an office room as 'good daylighting' for $UDI_{100\text{-}2000}$ values over 50% (subdividing this class into two further classes: $UDI_{100\text{-}2000}$ over 75% and $UDI_{100\text{-}2000}$ between 50% and 75%) and as 'poor daylighting' for $UDI_{100\text{-}2000}$ below 50% (subdividing this class into two classes: $UDI_{100\text{-}2000}$ between 0% and 25% and $UDI_{100\text{-}2000}$ between the range 25%-50%).

As final output, the performance of the two technologies was rated as an average of the 12 time-steps analyzed, in terms of both $E_{u\_100\text{-}3000}$ – DGP values, and in terms of occurrence of each class, expressed as percentage of occurrence with regard to the 12 time-steps.

3. Results

3.1. Detailed results of the 72 cases

Figure 2 shows the E_u and DGP results obtained from the Radiance simulations for the sample room. It emerges that the cases with the PCM always present higher E_{u_3000} values than the corresponding cases with the selective glass. The E_{u_100} reaches high values for the lowest sun positions only (or after the sunset): for these conditions, the the DGU with PCM show in most cases lower E_{u_100} values than the corresponding DGU with the selective glass. E_{u_3000} values are higher for the PCM technology than for the selective glass at 9:00, 12:00 and 15:00 for all the considered sites. The E_{u_3000} value is greatly influenced by the sun position in the sky, and therefore by the latitude of the geographical site. The difference between the E_{u_3000} values obtained for the PCM and for the selective glass may vary from less than 10% to more than 70%, depending on the time-step (day of the year, hour of the day). The cases with highest $E_{u\_100\text{-}3000}$ values refer to June 21st for Turin and Abu Dhabi, to Sept. 21st for Abu Dhabi and to Dec. 21st for Östersund, with the exception of 18.00 hours (i.e. a condition after the sunset). If on the one hand E_{u_3000} values are generally higher in the presence of the DGU with PCM compared to a DGU with selective glass, on the other hand the opposite occurs with the $E_{u\_100\text{-}3000}$ metric. For the same boundary conditions, the technology with PCM admits more daylight into the room compared to the technology with selective glass, resulting in higher E_{u_3000} and in lower $E_{u\_100\text{-}3000}$. This shows a potential increase in the discomfort problems when the PCM glazing is installed.

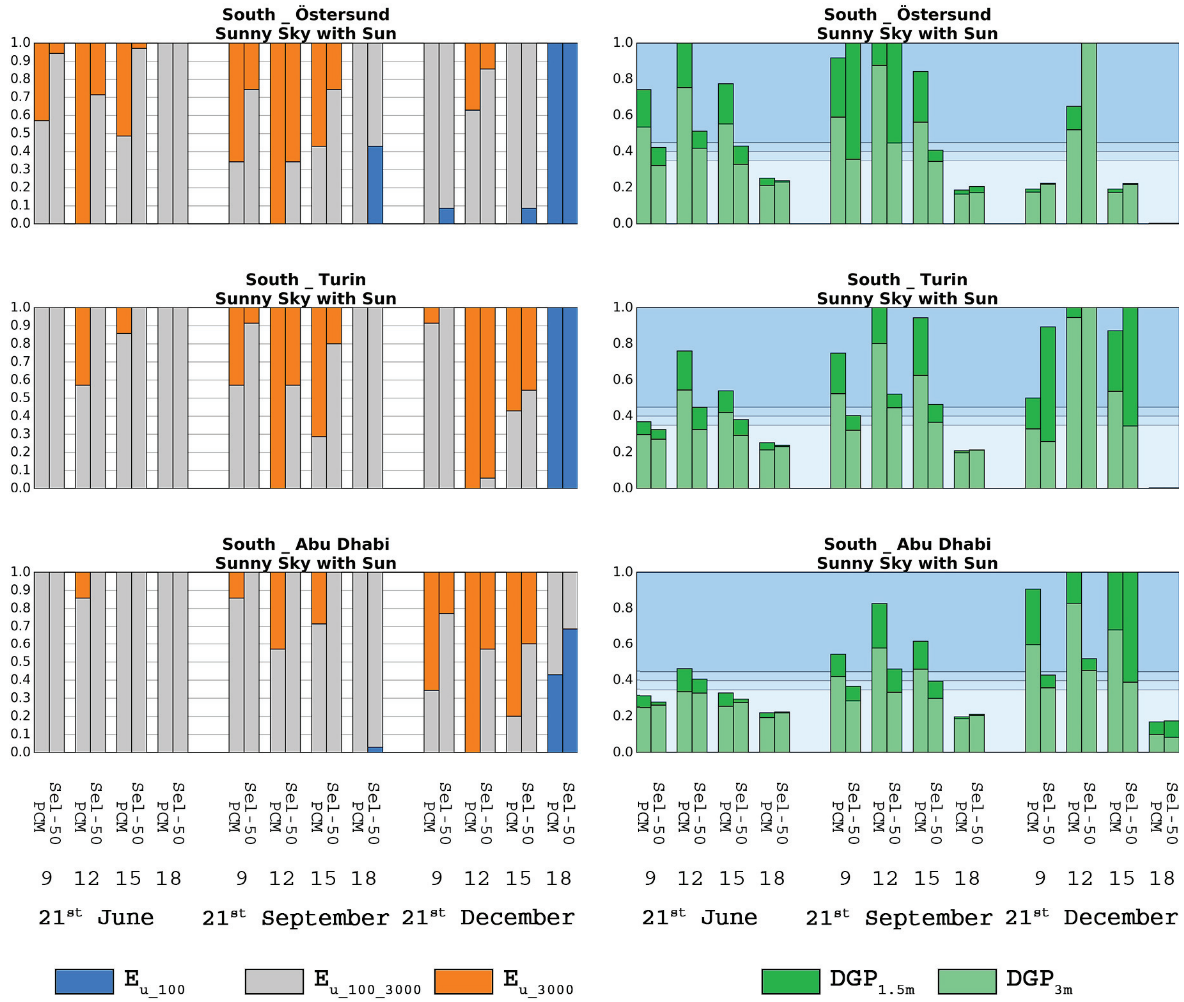

Fig. 2. E_u and DGP values for the whole database of results.

This behavior is confirmed by the analysis of the DGP values: for nearly all the cases analyzed, the DGP for the PCM is higher than for the selective glass. For most cases with an E_{u_3000} different from zero, the $DGP_{1.5m}$ is over 45%, while the DGP_{3m} is over 35%. For the selective glass, the $DGP_{1.5m}$ values are much lower compared to the cases with the PCM, but in any case lower than 45%, while for the DGP_{3m} it is possible to observe less discomfort situations (DGP>45%). The lowest DGP1.5m and DGP3m values were observed for June 21st in Abu Dhabi and for Dec. 21st in Östersund. For all the other days and sites, the DGP obtained for the PCM is always classified as intolerable for at least two out of four moments of the day analyzed.

The DGP follows the trend highlighted for the E_u: in fact, for the morning and noon hours, DGP is always lower than 35%, with the exception of Abu Dhabi at noon. On the contrary, the glare is often intolerable in the afternoon, with the exception of those cases where the sun is low on the horizon or has already set. The DGP values for the cases with the PCM are nearly always higher than the DGP for the selective glass (with the $DGP_{1.5m}$ nearly always higher than DGP_{3m}).

The different light transmission capability of the two technologies can also explain why some DGP results calculated for the PCM are lower than the corresponding values for the selective glass. For cases when the direct solar radiation hits the DGP calculation point, the DGP calculated for the selective glass is equal to 100%, while the DGP for the PCM, due to its diffusing transmission properties, is lower (though never lower than 45%).

Finally, it is worth highlighting that a strong correlation between the E_{u_3000} and DGP metrics is seen, as for the majority of the case studies when E_{u_3000} is different from zero, glare issues are registered too. This is in accordance with what highlighted by Mardaljevic et al. [32] as basis for the definition of the modified upper threshold of the UDI_{3000} (increased from 2000 lx to 3000 lx).

3.2. Synthetics representation of results into classes

Figure 3 shows the results of E_u and DGP metrics. From the data shown in the figure, it is possible to notice that the $E_{u,av\_100\text{-}3000}$ is always higher for the cases with the selective glass.

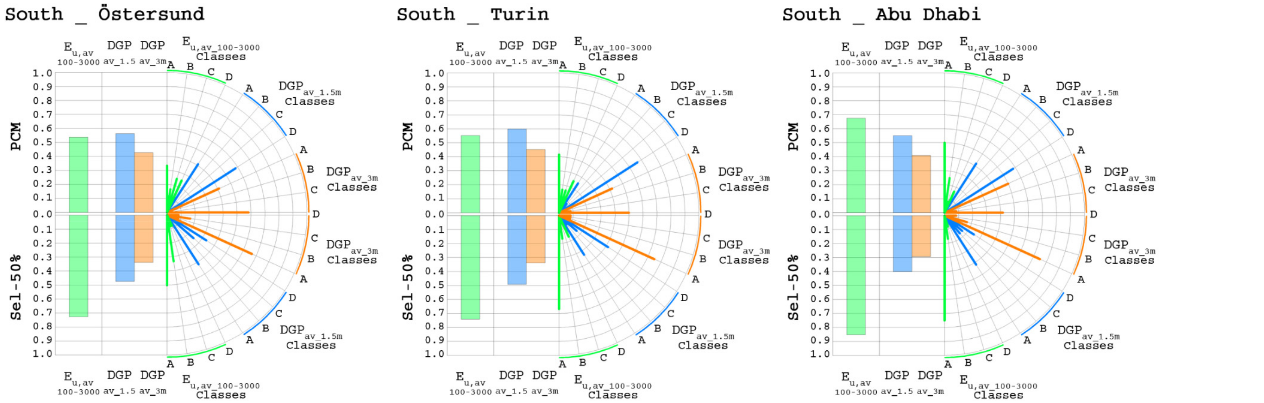

Fig. 3. Performance classes: $E_{u,av\_100\text{-}3000}$, $DGP_{av\_1.5m}$, DGP_{av_3m}, $E_{u,av\_100\text{-}3000}$ classes, $DGP_{av\_1.5m}$ classes and DGP_{av_3m} classes.

As far as the occurrence of E_u classes is concerned, it is possible to notice how, for every site, the cases with the selective glass show a better performance for classes A and B: this occurrence is higher than for the corresponding cases with the PCM. Conversely, the occurrence of classes C and D is lower. DGP_{av} values confirm what was observed for the $E_{u,av\_100\text{-}3000}$: in fact, both the $DGP_{av\_1.5m}$ and the DGP_{av_3m} are always higher for the PCM technology, for all the sites considered: in detail, for this technology the $DGP_{av\_1.5m}$ and the DGP_{av_3m} always exceed 45% and 35%, respectively.

The difference in the DGP_{av} values between the PCM and the selective glass technologies is in the range 8%-16% for the $DGP_{av\_1.5m}$ and 6%- 12% for DGP_{av_3m}. For both metrics, the difference seems to increase as the latitude decreases, following the trend found for the $E_{u,av}$. However, there seems to be no correlation between these values and the latitude of the site. As far as the occurrence of classes of $DGP_{av\_1.5m}$ and DGP_{av_3m} is concerned, it is possible to observe a better performance for cases with the selective glass, regardless of the site.

4. Discussion

This study has investigated the performances of a PCM-based glazing from a visual comfort perspective, a topic previously unaddressed in current literature. A novel method for data post-processing and performance evaluation was specifically developed for the study: this involves an existing metric (the DGP) coupled with a newly proposed metric (the 'useful illuminance', E_u). This metric was defined in a consistent way with the concept of the Useful Daylight Illuminance, a parameter that indicates that optimal lighting conditions for the occupants are achieved when the illuminance level lies in the range 100-3000 lx. The difference between the UDI and the E_u is that the UDI is a frequency throughout a year or other time intervals (or in other words, it is a temporal average of UDI values during time), while the proposed E_u has a spatial meaning, as it is a fraction of the work plane points for which the illuminance is in the comfort range 100-3000 lx. As a further step, the values of these metrics were synthetized into classes to allow a quick reading of the performance and a comparison with other technologies (for the case of this study, a selective glass was used as reference case). This methodology was conceived to be replicable, that is to be applied to other PCM or glazing technologies.

Parallel to the potentials, it is also worth stressing some limitations of the study. First of all, the PCM was assumed as constantly in its solid phase, as the purpose of the research was the analysis of the impact of its diffusing properties on the amount and on the directions of the daylight transmitted. This implied that the PCM was modeled as diffusing also for some time-steps during which the real material might be in a liquid state (for instance, late afternoon hours). It is clear, though, that a more realistic study of the actual transformation profile of the PCM could be developed, based on the characterization of a set of Bidirectional Scattering Distribution function BSDF to be used for annual simulations to account for the dynamic conditions of the PCM. Having the PCM in a permanent solid phase, with a Lambertian emission, made it possible to model the material in Radiance in a quite simple way, taking advantage of the inherent properties of trans materials. The outcomes obtained with this simplified theoretical approach can be considered as a starting point for a detailed study of the most problematic aspects of this technology, as for example its light distribution during the transient phases.

Another limitation is concerned with the reduced number of time-steps which were simulated in the study: three reference days during the course of the year, with four hours per each day. This was useful to test the methodology and to come up with a first assessment of the visual comfort performance of the PCM, and also to compare it to a reference technology. A more extended analysis of the annual performance of the PCM should be run to obtain more extensive results. However this approach is very complex as it is extremely difficult to characterize in detail the PCM transient phase, both from the thermal point of view (definition of the transition temperatures and the corresponding thermal properties to be assumed) and from the visual point of view (visible transmittance, light scattering properties and variable BSDF definition). An annual analysis should then be aimed at an optimization (goal), but, due to the many aspects involved, very different one from another (visual comfort, thermal comfort, building energy demand, etc...), it would be is by no means trivial the definition of a consistent optimization criterion according to which to carry out the study would be a very difficult task.

Furthermore, if a different technology from the selective glass with a T_v of 50% would be chosen as reference case, a different variation between the baseline behavior and PCM's would be observed.

The focus of the paper was placed on the behavior of the window system when the PCM layer is in the solid state. It is worth mentioning that previous analyses [28,29] showed that, when in the liquid state, visible transmission is enhanced, compared to a reference, conventional glazing with the same glass pane and without a PCM layer. This behavior, that may look odd at first sight, can be explained considering that the refractive index of the PCM layer is very close to that of conventional float glass. Such a feature has an impact on the optical losses due to the multiple, inter-cavity reflections at the air-glass interface, which are sensibly lowered. However, as mentioned in the introduction, a dedicated analysis of the impact of a liquid PCM layer on the luminous environment of an indoor space was not carried out. The reason for this choice is that in a well-design PCM window, the phase change material layer should avoid reaching the full liquid state to prevent a non-optimal performance [23].

Finally, it should be observed that both glazing systems were not equipped with any shading system. This choice was taken to assess the 'pure' performance of the two transparent technologies (a selective glazed unit and a PCM glazed unit) which are often meant to be used without additional shading devices.

As for the classes that were used in the study, it is important to notice that the classes based on the DGP limits defined in [10] were adopted as far as DGP is concerned, while for the E_u a set of classes was specifically introduced by the Authors. These classes are somewhat similar to the UDI classes used in [31], in terms of the intervals adopted, but have a different meaning. However, additional investigations might be necessary to assess their robustness and significance.

It is also worth stressing that the study has considered the E_u and the DGP as the only metrics to assess the visual comfort: other aspects, such as the luminance distribution and contrasts within the users' field of vision, as well as the possibility for the occupants to enjoy a view to the outside, have not been taken into account. Clearly, the presence of a PCM in the solid diffusing state would limit the view out. As a result, an optimized layout of the window could imply to limit the presence of the PCM to the upper and lower sections of the window, leaving a specular glazing in the middle section as a 'view glazing'. Furthermore, the users were assumed to have a direct view of the window, which is an unrealistic case. Normally, users have a view parallel to the window, and they change their position and view direction in response to discomfort glare throughout a space, according to the concept of 'adaptive zone', as described in [33].

5. Conclusions

In this paper the impact of a double glazed unit with PCM layer on the luminous environment and on the visual comfort potentially perceived in a space are presented. The PCM glazed component was analyzed in its solid phase (assumed as a constant) and compared to a reference standard double glazed unit equipped with a selective glass pane with a similar light transmittance. The visual comfort was assessed through two metrics, the DGP perceived at the occupants' eyes, and the 'useful illuminance', a new metric introduced by the Authors to analyze the spatial distribution of illuminances over the workplane. Due to its light transmission capability, the PCM component showed to generally admit more daylight into the space. However, this increased amount of natural light, observed for most of the geographical sites and time-steps considered, does not result, in general, in an increased visual comfort, in terms of both E_u and DGP. The PCM glazed systems shows an improvement of the visual comfort conditions, compared to the selective glazed unit case, only when the overall luminance of the portion of sky visible from the window is low. This condition occurs in case of sunny sky and sun low on the horizon – i.e. with a small incident angle, or when the sun is not directly visible from the window. Apart from these cases, for the other cases the performance of the DGU with PCM was found to be worse, in terms of both the E_u and DGP values, than in the cases of the DU with the selective glazing.

The overall best performance of the PCM glazed unit was observed for the northernmost tested location, Östersund, for which a result in line with the phenomena observed in case of low zenithal angles was found. However, even in this case, the reference case presents better visual comfort conditions.

The dependence of the results on the zenith angle opens up a particularly interesting investigation on methodologies to analyze visual comfort conditions through the use of sun position rather than sites and climates.

This preliminary study was useful to define and test a procedure to analyze the visual comfort concerned with PCM layers embedded in transparent façades. As future steps of the still on-going research, annual simulations will be used to calculate climate-based daylight metrics and the transient phase of the PCM will be introduced in the analysis workflow, coupling the annual temperature profile of the PCM layer to its transparency state (specular liquid, diffusing solid, transient) and hence to the light amount and distribution admitted into an indoor space. The concept of cylindrical illuminance will also be used in comparison and in integration of the DGP metric, as the cylindrical illuminance has the merit of being view-independent [34], which makes this metric suitable to account for the concept of 'adaptive zone' for visual comfort [33].

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