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Daylight availability in a room equipped with PCM window

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ABSTRACT
The increase in building energy performance mainly focused on the improvement of physical properties (thermal and optical) of individual components of building envelope. Very good isolation parameters can be easily achieved for opaque elements like walls and roofs. However, improvement of glazed component parameters is still required. Improving thermo-physical properties of window can be achieved using phase change material (PCM). Presented work is a part of extensive research project including the analysis and experimental investigation of window integrated with PCM layer. This modification changes the thermal properties of glass unit and effects on visible light transmission through the window.
The main purpose of the presented work is numerical analysis of the daylight conditions in the office room equipped with PCM window. The research was done for two geometrically identical indoor spaces varying by the window orientations: eastern and western respectively. Simulation was performed using a coupled validated simulation tools: ESP-r and Radiance. First software was used to model analyzed rooms then using second computational environment the illuminance and daylight factors in selected points were determined. Optical data of glazing unit equipped with PCM were appointed experimentally and adjusted to the numerical model. Simulations were carried out for characteristic sky conditions and selected days of year. Assessment of daylight availability in each room was done based on obtained values of illuminance and daylight factor in selected points. Five cases of the triple glazed window were considered: standard one and equipped with PCM layer positioned in the inner or outer cavity in liquid or solid state. Obtained results show that window with PCM in liquid state does not significantly reduce the daylight availability in room regardless the PCM position. However, window with PCM in solid state significantly decrease the light transmission through the window consequent in insufficient daylight conditions in analyzed rooms.

KEYWORDS
daylighting, PCM layer, light transmission, ESP-r, Radiance.

INTRODUCTION
Visually comfortable environment in building provide good ability to work and health of occupants. Appropriate visual conditions can be achieved by ensuring required lighting levels, illuminance uniformity and access to daylight. In traditional building the daylight availability is provided by the windows. However, glazing components are commonly the weakest building envelope element considering thermo-physical properties. One of the ways to improve the thermal capacity properties of window is integration of phase change materials (PCM) with glazing unit. Recently many studies about application of PCM in glazed elements of building envelope were published. The first article presenting parametric study of PCM glass system describes numerical and experimental investigation of window with PCM (Ismail and Henriquez, 2002). During last few years, many PCM technologies for the translucent and transparent building envelope, such as windows, shutters and other shading

devices (Silva et al., 2016) as well as roof glazing (Liu et al., 2018) were developed. Majority of the available researchers focuses on the analysis of thermal and optical parameters of PCM included into double glazing window on a laboratory scale (Gowreesunkera et al., 2013; Goia et al., 2014). Some of the studies consider adding of the additional container with PCM to double glazing window (Weinlader et al., 2005). Lastly, Giovannini et al. (2017) presents the analysis of impact of a double glazed unit with PCM layer in solid phase on the luminous environment and on the visual comfort in room equipped with such glazed unit.

Presented work is part of wider research project SOLTREN concerning the extensive analysis and experimental investigation of triple glazed window integrated with PCM layer considering effect of proposed solution on energy performance and visual comfort in experimental room. Double glazed windows have insufficient thermal properties in moderate and cold climatic conditions, therefore analysis of triple glazed window equipped with PCM layer is performed. Research described in this paper provides preliminary studies of impact of PCM layer on daylight availability in analyzed office room. Impact of PCM state, position in triple glazing unit and orientation of the window is considered.

METHODOLOGY

Analysis was performed using coupled ESP-r and Radiance tool. ESP-r, a modelling tool for building performance simulation, was chosen for energy analysis of proposed PCM window. Whole geometry and material properties was defined using ESP-r program. Subsequently, the simulation of daylighting was made by Radiance engine. Connection of ESP-r and Radiance allow calculating energy performance and illuminance simultaneously for one geometry model of analysed zone. However, ESP-r and Radiance coupling permit only for limited lighting analysis such as visualisation or calculation of illuminance and daylight factors for defined grid points. Glare can be calculated using only UGR coefficient which is not suitable to large-area light sources like windows (Carlucci et al., 2015). Therefore, in presented paper the daylight availability assessment will be made based on obtained illuminance and daylight factors.

Analysis was performed for 4 characteristic days of spring equinox, summer solstice, autumn equinox and winter solstice which occur respectively in March, June, September and December. In each selected day simulations were made for 3 characteristic hours during typical work profile for office: 9 a.m., 12 p.m. and 3 p.m.. In further part of paper each simulation step will be named by month and hour: III 9, III 12, III 15, VI 9, VI 12, VI 15, IX 9, IX 12, IX 15, XII 9, XII 12, XII 15. Furthermore, analysis was performed for two identical office rooms differentiated by the window orientation: eastern and western. Two standard sky conditions: CIE clear sunny and overcast sky was taken into account for all cases. The following 5 window types were considered:

- A - standard triple glazed window,
- B - triple glazed window filled with PCM in liquid state positioned in the outer cavity,
- C - triple glazed window filled with PCM in liquid state positioned in the inner cavity,
- D - triple glazed window filled with PCM in solid state positioned in the outer cavity,
- E - triple glazed window filled with PCM in solid state positioned in the inner cavity.

Window cavity filled with PCM was 16 mm depth. The characteristic of each glazed unit type were determined based on the previously performed measurements with experimental window component and artificial sun (Table 1). Cases A, B and C were modelled as glass material when cases D and E were introduced as translucent material.

Table 1. The characteristics of modelled types of windows

window case	A	B	C	D	E
light transmission [-]	0.71	0.64	0.55	0.06	0.03

Simulations for all described cases were made for 0.5 m density grid points filling the whole room and located at the height of working plane at the level of 0.75 m. Daylight factor and illuminance in all points for the clear sunny and overcast sky were calculated. Analysis of obtained results with particular attention on points located at the position of occupants working plane was performed.

CASE STUDY

Analysis was conducted for individual office cells representing the existing experimental office rooms. Dimensions of analysed zone are respectively width, length and height: 2.6 m, 4.4 m and 2.6 m. Window is situated in a centre of the exterior wall at the height of 0.7 m and dimensions of the glazed unit are 1.1 m of width and 1.1 m of height. Each office room is occupied by two workers. Both occupants working plane are located in the middle axis of the office room and at the distance of 1.5 m (1st working plane) and 3.0 m (2nd working plane) from the window. The RGB values of the interior surfaces of walls, floor and ceiling were determined based on the measurements using spectrophotometer Konica Minolta CM-2500d.

Analysis was performed for the location of the office rooms in the Central Europe under the temperate climatic conditions. Furthermore, analysed office rooms were located at the level of 4th floor which corresponds with real location of the experimental rooms.

RESULTS

Analysis of the obtained results was divided into three parts: comparison of the effect of PCM layer position on daylight conditions at first working plane, investigation of the illuminance distribution in whole room and detailed assessment of daylight availability in all considered simulation steps. Obtained results were named with two letters, first describe orientation and second type of window.

Daylight conditions at working plane for different position of PCM layer

Two positions of PCM layer were considered: in outer and inner window cavity. In Figure 1 are presented graphs of illuminance at 1st working plane obtained for windows with PCM in liquid and solid state positioned in outer and inner cavities of eastern oriented window for clear and overcast sky conditions.

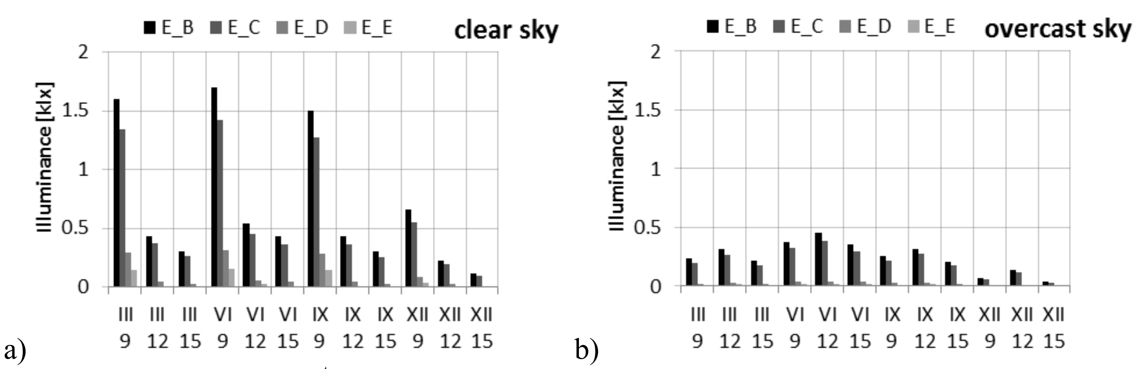

Figure 1. Illuminance at 1st working plane for eastern oriented window for a) clear, b) overcast sky conditions

It can be noticed that position of PCM layer has impact on illuminance calculated at working plane. Illuminance for cases with PCM located in outer cavity (B, D) is higher than for cases with PCM located in inner cavity (C, E) regardless the state of PCM. Described differences are the highest for clear sky conditions at 9 a.m. for all presented cases, which is caused by the solar beam radiation incident directly through the eastern oriented window. The same dependence was noticed for western oriented window at 3 p.m. For the other cases the divergences between illuminace calculated for both position of PCM layer is lower because of operation under only diffused solar radiation.

Illuminance distribution in analyzed office room

In Figure 2 were presented illuminance distribution in analysed office room with eastern orientated window (cases E_A, E_B, E_D) in spring equinox at 9 a.m. for CIE clear sunny sky. It can be noticed that illuminance distributions for cases A and B have a similar shape and only a level of illuminance for window with liquid PCM is slightly lower. However, distribution of illuminance in these cases in uneven, level of illuminance is very high near the window and significantly lower in further part of room, which may cause visual discomfort of occupants. On the other hand, illuminance distribution for case D is more uniform, however level of light at both working planes is too low considering minimal requirements of 500 lx for office work.

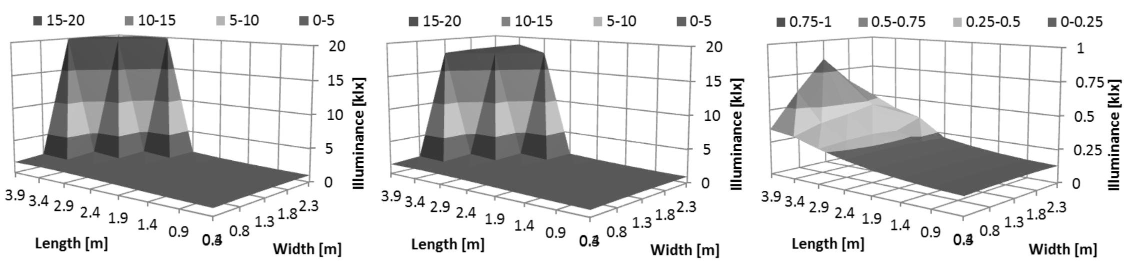

Figure 2. Illuminance distribution in analysed office rooms with a) A, b) B, c) D type of eastern oriented window in spring equinox at 9 a.m. and for CIE clear sunny sky.

Daylight availability at working plane

In last part of the paper the results of illuminance and daylight factors at 1st working plane were presented for the A, B, D type of window and both orientation: eastern and western (Figure 3). It can be seen that for clear sky conditions maximum levels of illuminance for eastern and western oriented windows occurs respectively at 9 a.m. and 3 p.m. according to operation of direct solar radiation. Nevertheless, maximum values of illuminance for cases with western oriented window are higher than for cases with eastern oriented window. Level of illuminance for other cases, when only diffused solar radiation operates, is comparable between eastern and western cases.

Considering illuminance requirements for office space at the level of minimum 500lx, it can be noticed that sufficient illuminance is reached only for clear sunny sky conditions (at 9 a.m. for eastern oriented window, at 3 p.m. for western oriented window and at 12 p.m. in summer solstice for both orientations) for cases of standard window and window with liquid PCM. Implementation of liquid PCM decrease illuminance in all cases, however it does not influence the number of cases meeting the requirements of 500 lx. Whereas cases with PCM layer in solid state influence significantly on illuminance level, in all cases below required 500 lx.

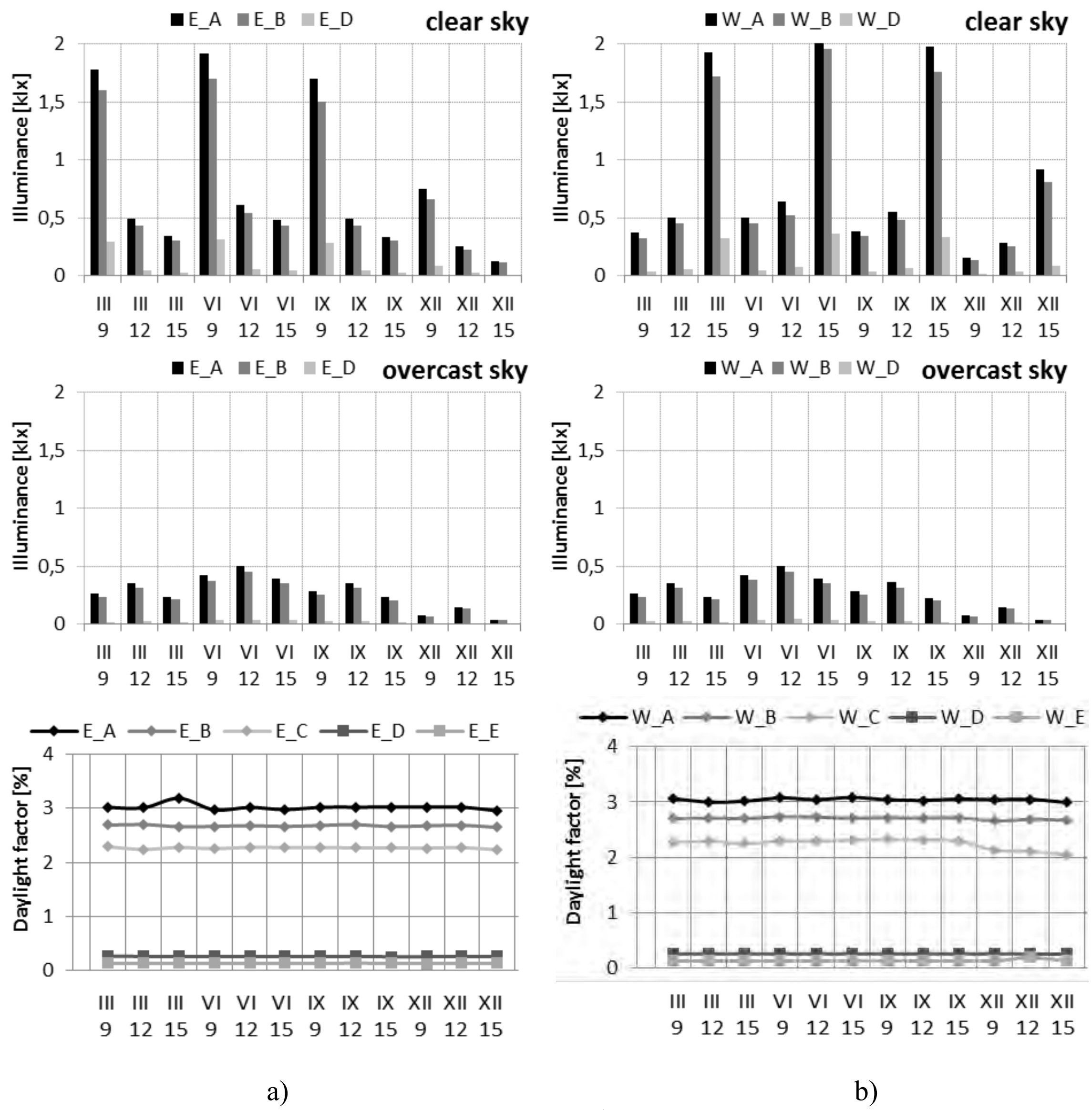

Figure 3. Illuminance and daylight factor and at 1st working plane for a) eastern, b) western oriented window.

Levels of daylight factors are constant during all analyzed days and hours with only slight fluctuations. Differences for eastern and western oriented window are insignificant. The daylight factor level for basic case with standard window reached averagely 3% for both orientations. Subsequently, daylight factor for cases with liquid PCM window are slightly lower – averagely 2.7% and 2.3% for window with PCM layer positioned in the outer and inner cavity respectively. Such level of daylight factors meets the requirements of minimum 2% at the working plane in the office area. Nevertheless, level of daylight factors for cases with solid PCM layer are significantly lower and not complete required level.

DISCUSSIONS AND CONCLUSIONS

Presented analysis focus on the assessment of daylight availability in a room with triple glazed window integrated with PCM layer. The application of PCM in window increases its thermal capacity but simultaneously decrease the light transmission through the window. Therefore, the analysis of the PCM application in glazing unit need to include the visual comfort assessment in area connected with modified unit. This topic was studied so far only by Giovannini et al. (2017), analysing impact of double glazed unit with PCM layer in solid phase on the luminous environment and the visual comfort in room under a clear sky and with the façade facing south. Considering different assumptions of presented study and mentioned Giovannini et al. (2017) research, results obtained from them are incomparable.

In presented research the daylighting availability in the office room were presented considering different types of triple glazed window: standard and filled with liquid/solid PCM positioned in interior/exterior cavity. It was observed that application of PCM layer into triple glazed window decrease the daylight transmittance of glazing unit causing reduction in the illuminance and DF in room. For liquid phase of PCM this reduction is small and not influences significantly the daylight distribution in interior. However, PCM in solid phase highly decrease the daylight transmittance and hence the illuminance distribution. Furthermore, analysis of PCM position indicates that position of the PCM layer in the outer cavity for both liquid and solid phase influence higher daylight availability than position of the PCM in inner cavity. In conclusion, application of PCM layer in glazing unit decrease the daylight availability in room equipped with such window. However, PCM window has high potential to improve the thermal capacity properties with insignificant influence on the visual comfort when it will be design to be melted during a day to ensure visual comfort in room.

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