Energy and Buildings 88 (2015) 110–121

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Development of a window shutter with phase change materials: Full scale outdoor experimental approach

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ARTICLE INFO

Article history:
Received 16 September 2014
Received in revised form 4 November 2014
Accepted 19 November 2014
Available online 4 December 2014

Keywords:
Energy performance
Heat flux
Indoor thermal comfort
Phase change materials (PCMs)
Thermal energy storage
Window shutter

ABSTRACT

The building sector is the largest final end-use consumer of energy in the European Union. Substantially heat losses occur through windows and translucent areas, therefore it is crucial to mitigate the energy transfer between these boundaries. The use of phase change materials (PCMs) is presently a good solution to improve the energy performance of building components, namely the glazing or window shutter protections.

It is presented and discussed an experimental campaign of a full scale outdoor test cell that is composed by two side-by-side compartments. The internal compartments were submitted to similar weather conditions in a Mediterranean climate during the winter season. The south oriented facade is a glazed area that incorporates a window protection system–window shutter. It was tested and compared two similar windows shutters, one containing PCMs and the other without PCMs (referred to as reference compartment).

During the experimental period the external air temperature fluctuated from 4.5 °C to 14 °C, which represent maximum thermal amplitude of 9.5 °C and the relative humidity ranged between 75% and 95%. The daily average solar radiation ranged from 25 W m^{-2} to 110 W m^{-2} and the maximum value reached was 310 W m^{-2}.

The maximum indoor air temperature measured of the compartment with the PCM shutter was 37.2 °C, which is 16.6 °C lower than the indoor air temperatures in the reference compartment that reached 53.8 °C. The minimum indoor air temperature for both compartments is similar, however the minimum air temperature of the reference compartment drops faster. The maximum heat flux on the internal wall surface of the compartment with the PCM shutter was 6.5 W m^{-2} and the minimum −3 W m^{-2} against 16 W m^{-2} and −8 W m^{-2} of the reference compartment.

The results reveal the PCM potential for the thermal regulation of indoor spaces as well as improving the energy efficiency of building spaces.

1. Introduction

The building sector is currently the single largest final end-use consumer of energy [1]. Until 2035 it is expected that the energy demand in this sector will grow at an average annual rate of 1%, so it is imperative to improve the energy efficiency of the building sector and decrease the energy consumption [1,2]. The European Union, to minimize and to improve the energy efficiency of the building sector applied some environmental targets and directives [3]. The reduction of the energy consumption for cooling and heating and the reduction of the energy needs are crucial to achieved the proposed targets [2].

1.1. Contribution of translucent areas of the building envelope

The glazed areas and the shading devices have a significant role over the energy building consumption, so many research studies and prototypes have been developed in the last years to increase the thermal and the energy efficiency of this boundary. The improvement of the thermal performance through the glazing area of the building can be attained resourcing to new materials, geometries and new techniques to produce solutions with higher energy

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http://dx.doi.org/10.1016/j.enbuild.2014.11.053
0378-7788/

efficiency. New approaches, as the building orientation and the use of natural resources, as wind and solar radiation could decrease the energy needs and improve the energy transfer of these boundaries. Some researches and experimental tests could be found in the references: venetian blinds [4–9], windows with roller blinds/shades [10–13], louver shadings devices [14–16], internal shading [17] and over-hangs [18].

1.2. Experimental and numerical studies of glazing and blind solutions

Grynning et al. [19] discussed what types of windows will be used in future buildings and tested and analysed the effect of the heat losses and the heat gains in a typical office building located in Norway. They used the building energy simulation software – EnergyPlus – and tested different thermal transmittance values (*U*-value) and solar heat gain coefficients (SHGC). Taken the overall results Grynning et al. [19] conclude that:

- The cooling and heating demand could be lower than zero if the SHGC present a lower value than 0.6 (using any *U*-value);
- The results obtained through all combinations converged to the same arrangement of *U*-value and optimal SHGC of $0.4\,W\,m^{-2}\,K^{-1}$;
- The discrepancies of the results between all methods is highest for the double-pane window and lowest for the four-pane window;
- The energy savings can increase 5% to 15% (dependent on the SHGC) and, if the *U*-value is reduced from 1.28 to $0.8\,W\,m^{-2}\,K^{-1}$.

Goia et al. [20] proposed a prototype of a simple PCM glazing system (DGU_PCM). They compared, during six months, relevant thermophysical properties and thermal performance (such as temperature, heat flux, and transmitted solar irradiance) between a simple PCM glazing system and the typical double glazed unit with common clear glass. They concluded that the indoor conditions reached by the application of the DGU_PCM solution increase considerably the thermal comfort comparatively to the conventional solution (DGU_CG) for all four seasons.

Grynning et al. [21] carried out an experimental study of a commercial double glazing system with an integrated solar reflection (prismatic glass, as presented by Christoffers [22]) and an internal spacer cavity of 23 mm filled with PCM. They conclude that the temperature stratification is higher than expected and probably due to the non-linear behaviour of the PCM. In example, at the scenario with solar irradiance of $1000\,W\,m^{-2}$ and indoor and outdoor air temperature defined to 24 °C, the temperature difference between the up and down of the surface is about 4 °C to 6 °C (exterior surface) and 2 °C (interior surface).

Kara and Kurnuç [23] presented an experimental study of the performance of a PCM trombe wall composed by a novel triple glass (NTG) and a plasterboard containing PCMs. To evaluate the performance of the PCM wall, they built a test room and carried out an outdoor test of a south-facing external wall during a whole year. A novel triple glass and a plasterboard containing PCMs compose the external wall. The PCM of the plasterboard was the Rubitherm® GR41 and GR35, which are composed by granulated encapsulated paraffin. The results show that the heat load provided by the PCM wall in October and November was 70% and 41%, respectively. Analysing the results on an annual basis, the ratio of solar energy gains from the PCM wall provided 14% of the heat load demand.

Wang et al. [24] evaluated the total heat flux through a glazing surface according to three main factors: (i) the influence of the radiation transmittance; (ii) the effect of the convection heat transfer coefficient; and the (iii) influence of the thermal amplitude between the temperature of the interior and the surface. Wang et al. [24] developed a mathematical model for the heat transfer that evaluated with good agreement the effect of (i) the glass properties; (ii) the convection heat transfer coefficient; (iii) the surfaces temperatures; and (iv) the air temperature. The main results show that:

- The influence of the solar radiation through the glass is significant for the heat flux increment.
- If the difference of temperatures, between the surface and the air (from the inside to the outside of the room) do not exceed 2 °C, therefore the total heat flux effect can be neglect.
- The convection heat transfer coefficient do not effect significantly the overall heat flux.
- Heat transfer is improved by the solar radiation in winter but has an adverse effect in summer.

Gomes et al. [5] determined both solar and visible properties of a glazing system with venetian blinds using a net radiation method. They compared the numerical results with the experimental data measured from an outdoor test cell. They concluded that the developed model can be used to simulate different system configurations, such as glazing and/or shading devices (including venetian blinds) and the model can be introduced into building energy simulations and building design tools. The numerical results were compared with the experimental data and for overcast sky conditions. For these conditions they got excellent fitting results, but for the clear sky conditions the comparison of the results presented some discrepancies. A venetian blind control strategy was used and they conclude that is more important for southern European regions. To help designers and users to improve the thermal and daylighting indoor conditions they presented some design plots with information about how to adjust the slat orientation of the venetian blinds.

Diarce et al. [25] presented an experimental and numerical study of a ventilated active facade with PCM incorporation on its external layer. The experimental results showed that for days with high radiation the temperature of the circulating air increased the test cell indoor temperature in average about 10 °C to 12 °C. As they explained, the ventilated facade without PCM can also warm up the air, however the PCM effect extends the heated period. When the solar radiation drops the ventilated façade with PCM keeps the indoor air temperature warming up after 2.5 h above 2 °C. The authors estimated that the energy efficiency of the ventilated active facade with PCM increased 10% to 12%, compared with the same model without PCM.

Gowreesunker et al. [26] evaluated the performance of a PCM-glazed, aiming particularly at the thermal and optical characterization of the PCM. They used the PCM Rubitherm® RT27 and the main conclusions were:

- The PCM-glazed is translucent in the liquid phase and transparent in the solid state.
- Under stables conditions, the visual PCM transmittance is 90% (liquid phase) and 40% (solid phase).
- The PCM increases the thermal mass of the solution, but this phenomenon is valid during the phase change process. When the PCM is in the liquid state (charged) the overheating risk increases.

1.3. Challenges and future role of glazed building areas

The previous sub-sections presented the importance of the translucent areas and identify relevant experimental and numerical studies. Large glazed areas dominate presently the new building design and as the most authors of previous research explain and