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Thermal and electrical performance of an integrated PV-PCM system in double skin façades: A numerical study

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ABSTRACT

In this article the performance of a system that integrates a photovoltaic (PV) layer and a phase change material (PCM) layer in a double skin façade (DSF) is investigated. A physical–mathematical model is developed to simulate the dynamic thermal behaviour of the system, and numerical simulations are carried out for different climates (Venice, Helsinki and Abu Dhabi) in order to evaluate the performance of the proposed solution. The numerical model combines different validated codes for the simulation of optical, thermal, and electrical behaviour of PCM, PV and DSF. The model is then coupled with the indoor air heat balance equation to evaluate the impact of the proposed façade system on the heating and cooling energy demand.

The adoption of a PCM layer in the DSF cavity, in combination with a semi-transparent PV layer, leads to a reduction in the monthly cooling energy demand in the 20–30% range. This result is particularly relevant for hot climates – where cooling loads are seen throughout the year. The improvement in terms of heating load in more cold-dominated locations is limited. The smoothing of the PV module temperature leads to an increase in the electrical energy converted by the PV, with peak values of improvement in the range of 5–8% when the DSF is equipped with the PCM–PV configuration. Ventilation strategies of the façade cavity, coupled with the correct selection of PCM (and of its transition-phase temperature range), are the key aspects to ensure effective management of the proposed technology.

1. Introduction

1.1. Background

Thermal energy storage (TES) systems could be used to reduce a building's dependency on fossil fuels and to contribute to a more efficient environmental energy use. The main advantage of using TES is that it can help with matching supply and demand when they do not coincide (Mehling and Cabeza, 2008). Thermal energy storage could be accomplished using either sensible or latent TES: sensible heat storage has been used for centuries by builders to store/release thermal energy, but a much larger volume of material is required to store the same amount of energy in comparison to latent heat storage (LHTES). An example of this is the use of a phase change material (PCM) as a storage medium (David et al., 2011). A PCM solidifies when cooling resources are available and melts through thermal energy absorption, thus reducing cooling loads (Soares et al., 2013). Within the building sector, the incorporation of PCMs to different construction elements or HVAC components can increase the thermal capacity of the building and thus contribute to reducing indoor temperature fluctuation, reducing heating and cooling loads and lowering energy use (Cui et al., 2015).

To enhance the energy storage capacity of a transparent building envelope component, Goia et al. (2013, 2014) have compared a conventional double glass unit (DGU) with a PCM-integrated DGU, and it was found that the higher the outdoor solar radiation, the greater the benefits on thermal comfort and energy performance that are achieved through the DGU_PCM due to shading and energy buffering effects provided by the paraffin layer. Weinlader et al. (2005) have investigated the thermal and optical performance of façade panels using a PCM. It was concluded that such integration improves thermal comfort, reduces heat gains through the course

Abbreviations: ASTF, active solar thermal façade; BIPV, building integrated photovoltaics; DGU, double glazed unit; DSF, double skin façade; HVAC, heating, ventilation and air conditioning; LHTES, latent heat thermal energy storage; PCM, phase change material; PV, Photovoltaics; TES, thermal energy storage.

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Nomenclature

A	cross sectional area (m^2)
A_{pv}	PV module cross sectional area (m^2)
$Abs(i)$	absorbed solar radiation in glass layer (i) (W/m^2)
a	solar absorption coefficient (–)
a-si	amorphous silicon
C	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
C^*	equivalent specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
d	optical thickness (–)
hc	convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h	specific enthalpy of fusion ($kJ\,kg^{-1}$)
h_o	outside convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_i	inside convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
H	height of the façade (m)
IL	internal loads (W)
I	impinged solar radiation (W/m^2)
I_{sc}	short circuit current (A)
K	thermal conductivity coefficient ($W\,m^{-1}\,K^{-1}$)
L	length of the plate (m)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
P	power (W)
Q	thermal loads (W)
r_n	reflectivity of surface n (–)
Re	Reynolds number (–)
Ra	Rayleigh number (–)
R_C	specific convection thermal resistance ($m^2\,K\,W^{-1}$)
R_K	specific conduction thermal resistance ($m^2\,K\,W^{-1}$)
R_{rad}	specific radiation thermal resistance ($m^2\,K\,W^{-1}$)
S	physical thickness (m)
T	temperature (°C)
V	air velocity ($m\,s^{-1}$)
V_{oc}	open circuit voltage (V)
x	layer thickness (m)

Greek symbols

β	liquid fraction (–)
δ	overall fractional change in transmittance (–)
ΔT_h	temperature range of phase change (°C)
ΔP	specific power ($10^{-1}\,W/m^2$)
ε	emissivity (–)
η_{PVm}	PV module efficiency (–)
η_r	PV module reference efficiency (–)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
v	wind velocity ($m\,s^{-1}$)
ρ	air density ($kg\,m^{-3}$)
σ	Stefan-Boltzmann constant, 5.67×10^{-8} ($W\,m^{-2}\,K^{-4}$)
$\sigma_{\varepsilon,l}$	extinction coefficient, liquid phase (m^{-1})
$\sigma_{\varepsilon,s}$	extinction coefficient, solid phase (m^{-1})
τ_r	transmission coefficient (–)
$\tau\cdot$	time step (s)
ψ	temperature coefficient of PV module (°C $\%^{-1}$)

Subscripts

c_1	air cavity 1
c_2	air cavity 2
g_n	glass layer number
i	indoor
l	liquid state
m	melting peak
o	outdoor
P	PCM node
PVm	PV module
r	reference
s	solid state

Superscripts

$^\circ$	previous time step
$*$	equivalent

of the day while overnight, non-desired heat gains can be drawn off. Silva et al. (2002) have analysed the dynamic thermal behaviour of a latent heat thermal energy store within PCMs both numerically and experimentally. The study highlighted the importance of each heat transfer mechanism and concluded that the initial charge period, and almost all discharge process are dominated by heat conduction. Melting time is dominated by the imposed heat flux and PCM thickness, while the solidification time depends only on the number of thermal units, i.e. the convective heat transfer rate and PCM thickness. Kuznik and Virgone (2009) have highlighted the importance of the hysteresis phenomena and the need to take them into account in order to predict the thermal behaviour of the PCM composite.

The adoption of PCM in buildings is an effective way to enhance the integration of technologies for renewable energy conversion through a better exploitation of solar energy, both through passive components (e.g. PCM in glazing systems and in walls) and active components (e.g. PCM in HVAC systems or advanced building envelope systems). The effects of the semi-transparent property, the PCM thickness, and the zenith angle on thermal performance of a PCM-filled double glazing roof was investigated numerically in Liu et al. (2016). It was concluded that the effect of thickness of double glazing roof on its thermal performance is large, with an increase in thickness resulting in an increase in temperature time lag.

One particular use of PCM in combination with other technologies for solar energy conversion is seen in its use for moderating temperature rise in PV modules, where efficiency loss due to the increase in module temperature can be reduced: in crystalline silicon solar cells, the associated elevation of PV temperature reduces the solar to electrical energy conversion efficiency by 0.4–0.5%/K (Batagiannis and Gibbons, 2001). Ciulla et al. (2012) have presented a one-dimensional thermal analysis of an isothermal PV-PCM model by using an explicit finite-difference approach. The numerical model results have been validated against experimental data obtained from a test facility in Palermo, Italy. The model can be then used to determine the thermal behaviour of a multilayer (opaque) wall in which there is a PCM coupled with a PV module. Aelenei et al. (2014) analysed a simplified thermal network model for building integrated photovoltaic BIPV-PCM which has been developed in MATLAB 6.1 (2000) and has been validated with experimental results during the heating period. The comparison has demonstrated a good agreement, with most discrepancies occurring when airflow begins to flow into the gap. The maximum electrical efficiency of the PV system reached 10% and the thermal efficiency reached 12%. Hasan et al. (2014) have investigated the economic consequences of applying PCM in a PV system in two different weather conditions. It was concluded that such a system is financially viable in higher temperature and higher solar radiation environments.