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Thermal behavior of a translucent superinsulated latent heat energy storage wall in summertime

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HIGHLIGHTS

- TIM-PCM wall provides heat storage/release, heat/sound insulation, and daylighting.
- In-situ experimentations carried out in Sophia Antipolis, France.
- Numerical model of the heat transfer through the wall is developed.
- The model of the wall linked to TRNSYS is validated experimentally.
- Thermal comfort with TIM-PCM wall ensured using shading devices or nocturnal ventilation.

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ABSTRACT

This paper investigates the thermal performance of a translucent solar wall providing, concurrently, storage and restitution of heat, super thermal-acoustic insulation and daylighting to the interior environment. The wall is composed of glazing, silica aerogel used as a transparent insulation material (TIM) and glass bricks filled with fatty acid, an eutectic phase change material (PCM). To assess the TIM–PCM wall thermal behavior, experimentations were conducted in-situ in a full-sized test cell located in Sophia Antipolis, southern France. Experimental data shows that the tested wall is more effective in winter and might cause overheating during the summer mainly due to solar gains and un-cycling behavior of PCM which remains in liquid state. To enhance the energy performance of the wall in summertime, a numerical model describing the heat transfer mechanisms occurring in the PCM layer in combination with the other transparent wall layers is developed. Then, the model of the wall is linked to TRNSYS software to assess the thermal performance of the whole building. The numerical model is validated experimentally and a good agreement is shown comparing the simulated values with the measured data for seven consecutive days in summer and winter. The importance of considering the natural convection effect in the liquid PCM is also demonstrated. Moreover, it was shown that shading devices can effectively reduce overheating while natural night ventilation decreases the indoor temperature without affecting the PCM performance since the outdoor temperature is always higher than the phase change temperature. The use of a glass with selective solar reflection properties depending on the season instead of the ordinary glazing is shown also to be very effective way to overcome the overheating problem. Finally, the TIM-PCM wall is tested under different climate conditions and passive solutions are given to ensure thermal comfort in summer season.

1. Introduction

Buildings account for almost 41% of the world's energy consumption, which contributes to 30% of the annual greenhouse gas emissions [1]. Trombe wall integrating phase change materials (PCM) is a particular passive solar technique that has shown great potentialities and can reduce effectively the building energy consumption. Basically, traditional Trombe walls [2–6] consist of an external glazing, an air channel, and a high heat capacitance wall in contact with the indoor environment. To improve the Trombe wall heat storage performance,

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Nomenclature

ACH	air change per hour
averfl	average fraction of liquid in the PCM layer
c_1, c_2, c_3	dimensionless coefficient (Eq. (37))
CFD	computational fluid dynamics
Cp	specific heat capacity (J/kg K)
CSTB	scientific and technical center for building research
d	optical thickness
e_i	experimental value
EN	European norm
f_l	liquid fraction
H	height of the vertical surface (Eq. (21)) (m)
h_{in}	indoor convective coefficient (W/m^2 K)
h_{out}	outdoor convective coefficient (W/m^2 K)
HVAC	heating, ventilation and air conditioning
k	thermal conductivity (W/m K)
L_H	latent heat of fusion (J/kg)
N	total number of nodes in each layer
Nu_z	Nusselt number function of z, Table 5
OP	overhang projection (m)
PCM	phase change materials
PERSEE	center for processes, renewable energies and energy systems
PRMSE	percentage root mean square error
$Q_{sol\text{-}ref}$	reflected solar radiation (W/m^2)
$Q_{sol\text{-}total}$	total incident solar radiation (W/m^2)
$Q_{sol\text{-}trans}$	transmitted solar radiation (W/m^2)
R	thermal resistance (m^2 K/W)
RIM	radiosity irradiosity method
RMSE	root mean square error
RTE	radiative transfer equation
S	physical thickness (m)
s_i	simulated value
T_{air}	outdoor air temperature (°C)
TIM	transparent insulation material
T_m	melting temperature (°C)
v	wind velocity (m/s)

Greek letters

$\varnothing_{LW,in}$	radiative heat exchange with the indoor environment (W/m^2)
$\varnothing_{LW,out}$	radiative heat exchange with the outdoor environment (W/m^2)
$\varnothing_{cond}$	conductive heat flux (W/m^2)
$\varnothing_{sol}$	radiative source term (W/m^2)
α	thermal diffusivity (Table 1) (m^2/s)
α	solar absorptivity coefficient
β	thermal expansion coefficient (1/K)
δ	fractional change in PCM transmittance
Δt	time increment (s)
ε	surface emissivity
ρ	solar reflectivity coefficient
ρ	density (Table 1) (kg/m^3)
τ	solar transmissivity coefficient
σ	extinction coefficient

Subscripts and superscripts

enh,p	enhanced at node p
in	indoor
l	liquid
pc	phase change
s	solid
sol	solar
surf	surface
W, e	west, east interface
W, E, P	west, east, center node

phase change materials were implemented in the wall composition and this technique has been investigated by numerous researchers [7–12]. During the day, this wall is heated due to the incident solar radiation, melting the PCM. While at night, when the outdoor temperature falls below the phase change temperature, the heat stored by the PCM is released warming the building. Fiorito (2012) [8] conducted a parametric study on the use of PCM in Trombe walls by varying the PCM position and the melting point temperature for five different climates they found enhanced performances for the modified Trombe wall. Zalewski et al. [9] studied experimentally a Trombe wall with PCM components filled in the air channel and an insulating board replacing the high capacitance wall. They found that the heat storage capacity of the wall is increased. Also, an experimental Trombe wall (ventilated façade) with PCM was studied by De Gracia et al. [10] during winter season. They found that the use of the ventilated facade with PCM improves significantly the thermal behavior of the whole building. Kara and Kurnuç [13] investigated a PCM Trombe wall with a novel triple glass (NTG) to improve the performance of conventional Trombe wall system and overcome its main disadvantage: the overheating during the summer. However, in all these applications, the light transmission was still absent.

On the other hand, transparent envelope components are key elements in buildings, especially in offices and commercial buildings, that affect the energy performance and daylighting [14–16].

The integration of PCM in a transparent element of the building envelope enhances the ability of energy storage, since the PCM will be directly exposed to the solar radiation. This technology aims to smooth the indoor temperature, and decrease the energy fluctuations, providing daylighting at the same time.

Phase change materials were integrated within double [17,18] or triple glazing units [19], within more complex glazing components [20] and within translucent solar walls [21]. The performance of glazing with integrated PCM was investigated both experimentally [17–19, 22, 23] and numerically [24–26]. Numerical models were specifically developed to take the interaction of PCM with solar radiation into account [27–30]. All numerical models developed in these studies neglected effect of natural convection in the liquid PCM. A literature review of the use of PCM in transparent and translucent building envelope components can be found in [31].

Manz et al. [21] studied a translucent wall for solar heating and daylighting composed of glass pan, air gap, a translucent PCM and a transparent insulation material (TIM). They investigated experimentally the optical PCM properties and a prototype of the TIM-PCM wall was constructed in 1994 in Swiss. Also, a one-dimensional numerical model (side effects were neglected) was developed considering only heat transfer by conduction and the optical properties were simulated using a Monte Carlo technique. The results show that the thermal and optical performance of the wall is very promising and that the chosen PCM in solid state reduces the heat and light gains, thus they proposed considering another PCM with a melting temperature of 21 °C instead of 26.5 °C. Weinläder et al. [32] investigated experimentally the thermal behavior of three glazing systems incorporated with a plastic container filled with different PCM. However, in both studies the behavior of the system was not investigated in detail in the hot season and inferences on thermal comfort were not evaluated according to standards. To improve the poor thermal inertia of conventional glazing systems, Goa