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A numerical and experimental study of a cellular passive solar façade system for building thermal control

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ABSTRACT

About 39% of total energy in the United States is consumed in residential and commercial buildings. Passive Solar Design (PSD) strategies have been successful in reducing building energy consumption, however, they require a substantial design effort for each individual project and are also difficult to implement in building retrofit projects. These characteristics tend to inhibit the widespread use of PSD principles in buildings today. In this paper a building envelop system is presented that incorporates small air cells backed by phase change material. The goal is to achieve quasi-constant core temperatures within a building enclosure system. The proposed technology results in a cladding system that can be used to thermally condition buildings. Initial experimental and numerical research efforts show that the system has significant potential to function properly when exposed to winter conditions. While initial results are promising, the system will require dynamic response to function properly in both winter and summer conditions.

1. Introduction

Energy consumption in residential and commercial buildings currently stands at about 39% of total energy consumption in the United States (Berry and Michaels, 2012). PSD (Passive Solar Design) strategies, operating at whole building scale, seek to reduce building energy consumption by balancing heat transfer across the building envelope with solar energy input, while also using thermal mass and/or ventilation to dampen diurnal external influences (Sadineni et al., 2011). PSD has been used in buildings ranging in size from small-scale residential projects to large-scale multistory buildings (Kruzner et al., 2013; Samuel et al., 2013), and the approach has been shown applicable to different climate types (Ralegaonkar and Gupta, 2010). PSD strategies are however highly sensitive to meteorological factors and thus require a thorough understanding of climatic factors and the use of building energy simulation tools (Ralegaonkar and Gupta, 2010; Stevanovi, 2013). It is also difficult to implement PSD strategies into older existing buildings, which are responsible for the bulk of building-related energy expenditures both globally and in the US (Stevanovi, 2013) These characteristics tend to inhibit the widespread use of traditional PSD principles in buildings today (Sadineni et al., 2011).

The past decades have also seen steady development of various technologies aimed at applying PSD at the scale of the building envelope. Some notable examples include Trombe walls (Saadatian et al., 2012), transparent insulation systems (Kaushika and Sumathy, 2003; Sharma and Kaushika, 1987; Wallner et al., 2006; Cadafalch and Cònsul, 2014), double skin façades (Shameri et al., 2011; Gratia and De Herde, 2004; Fallahi et al., 2010), ASTF (Active Solar Thermal Facades) (Ma et al., 2015), and PCM (Phase Change Material) (Kuznik et al., 2011). A Trombe wall can reduce building energy usage up to 30% (Hordeski, 2004). However, Trombe walls suffer from two key shortcomings. Trombe walls have low thermal resistance, causing a negative heat flux during prolonged cloudy periods (Chan et al., 2010; Shen et al., 2007; Zamora and Kaiser, 2009), and they are also difficult to control due to the unpredictable nature of the weather (Chan et al., 2010; Onbasioglu and Egrican, 2002). Transparent insulation combines the advantages of opaque insulation with solar collection (Kaushika and Sumathy, 2003; Sharma and Kaushika, 1987). This was initially used as convection suppressant devices to improve the efficiency of solar energy collectors (Francia, 1961; Veinberg and Veinberg, 1959), although lacks a mechanism to control the thermodynamics of the building envelope. Multiple ASTF systems have also been tested, some of which are an adaptation of traditional double skin façade systems. Most can be categorized as Building Integrated Solar Thermal, Building Integrated Photovoltaic, or a combination thereof. The active component lowers

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Nomenclature

α	surface absorptivity
ΔT_{pc}	phase transition temperature range
κ	attenuation coefficient
λ	wavelength
μ	dynamic viscosity
ρ	density
Σ	building enclosure tilt angle
$\mathbf{g}$	gravitational constant
$\mathbf{u}$	velocity, vector
ε	surface emissivity
φ	surface azimuth angle
$B_{sol,h}$	specular solar irradiance on a horizontal plane
c_p	specific heat capacity
$c_{p,app}$	apparent heat capacity
d_{cell}	air cell diameter
$D_{sol,h}$	diffuse solar irradiance on a horizontal plane
$e_b(T)$	blackbody hemispherical emissive power
G	irradiance
G_m	mutual irradiation between different exposed surfaces
G_{sol}	solar irradiance
$h_{ext,f}$	external surface forced heat transfer coefficient
$h_{ext,n}$	external surface natural heat transfer coefficient
h_{ext}	external surface heat transfer coefficient
h_{int}	internal surface heat transfer coefficient
$Height$	internal ceiling height
I	radiative intensity
$I(\Omega)$	radiative intensity at angle Ω
J	radiosity
k	thermal conductivity
l_{cell}	air cell length
LH	latent heat capacity
N	opaque sky cover
p	pressure
RH	relative humidity
T	temperature
t	time
$T_{a,cell}$	average air cell temperature
$T_{a,ext}$	external air temperature
$T_{a,int}$	internal air temperature
t_{cover}	thickness external cover plate
T_{dp}	dewpoint temperature
t_{ins}	thickness insulation backing
T_{pcm}	average PCM temperature
T_{pc}	phase transition temperature
T_{sky}	sky radiative temperature
T_{sur}	temperature of surrounding surfaces
v_w	wind velocity, scalar
w_d	wind direction

the incident solar gains, thus decreasing building cooling loads (Lai and Hokoi, 2015; Quesada et al., 2012a,b). Building integrated solar energy collectors however suffer from integration issues (Buker and Riffat, 2015) that lead to high cost and relatively low system efficiency (Quesada et al., 2012b).

PCM is often employed within PSD systems to buffer solar energy, allowing for a more efficient bridging of periods with low solar insolation (Baetens et al., 2010; de Gracia et al., 2015; Boukhris et al., 2009). The most common categories of PCM are: (i) organic compounds, such as paraffins and fatty acids, (ii) inorganics, like hydrated salts, and (iii) eutectics and their mixtures (Tatsidjodoung et al., 2013). Organic PCMs tend to have the advantage of being none-corrosives, low to no subcooling, low thermal conductivity, and long-term chemical and thermal stability, which is in contrast with inorganic PCMs. The advantage of inorganic PCMs is the greater phase change enthalpy ($350\ \frac{\mathrm{MJ}}{\mathrm{m}^3}$) over organic PCMs ($150\ \frac{\mathrm{MJ}}{\mathrm{m}^3}$) (Cabeza et al., 2011).

Various solutions have been developed to improve the performance of passive solar systems (Wallner et al., 2005a,b). Notable is the development of low-e (low emittance) coatings (Cuce and Riffat, 2015; Ebisawa and Ando, 1998), with a typical emissivity of 0.04 (Ebisawa and Ando, 1998) to 0.18 (Schaefer et al., 1997). However, solar spectrum transmittance of low-e coatings tends to fall between 0.60 and 0.75, which is a key drawback when harvesting solar energy. In ongoing solar energy collector research, AZO (Aluminum-doped Zinc Oxide) and ITO (Tin-doped Indium Oxide) coatings are optimized for such applications (Al-Mahdouri et al., 2014; Giovannetti et al., 2012). Total emissivities between 0.20 and 0.30 have been reported in combination with a solar transmittance of 0.85 or higher. An AR (Anti-Reflective) coating (Chen, 2001; Rosencrantz et al., 2005; Hammarberg and Roos, 2003) with a low refractive index is, however, necessary in combination with the AZO or ITO coatings in order to obtain such a performance (Giovannetti et al., 2012).

This study is an investigation into the application of solar energy harvesting in combination with PCM at the mm to cm scale, rather than the whole building or building envelope scale. The system under consideration is composed of small cellular air pockets with transparent front-cover, which convert solar irradiance into heat, backed by the heat buffering capacity of PCM pockets (see Fig. 1). The energy harvesting effect within the system is regulated by the application of opaque walls in between the air cells, causing a more shallow penetration of solar radiation during summer conditions compared to winter conditions. The solar energy admittance rate and energy loses are further regulated using various coatings applied to the system. Choosing a specific cell geometry that optimizes the convective flow within, and thus optimizing heat transfer from the air cell towards the external environment.

With sufficient heat capacity (sensible or latent) and control features it becomes possible to minimize the heat flux across the building envelope, and thus realize a passive zero-energy building enclosure system.

The research goals of this paper are to: (i) investigate the impact of certain system parameters on the behavior of the system, such as cell geometry, properties of the PCM, and the application of coatings on the external cover, and (ii) to investigate what shortcomings can be observed.

A numerical modeling framework is presented (Section 2) to investigate the sensitivity of these parameters. Experiments have been carried out to help investigate system behavior, and to validate the numerical model (Section 3). A parametric study was performed to fulfill these research goals (Section 5). We conclude by describing general behavior of the system and its potential for further development (Section 7).

2. Finite element modeling

A numerical model has been developed to investigate the potential of the proposed cellular façade concept. A simplified 2D geometry is used to reduce complexity. A schematic of the geometry and mesh are depicted in Fig. 2.

The necessary weather parameters to run the model are external air temperature, $T_{a,ext}$, relative humidity, RH, wind velocity, v_w,