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Optimization of latent heat storage in solar air heating system with vacuum tube air solar collector

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Abstract

This paper presents the design and modelling of the heat transfer of a solar air heating system, which consists of a vacuum tube air solar collector (SC) and latent heat thermal energy storage (LHTES), and a parametric analysis of the performance of this system. LHTES is a form of short-term daily storage that stores the SC heat during the day and releases it into the building during the night. Especially in low energy buildings with a high share of passive heating, this can significantly improve the utilization of solar energy for heating. The design of concentric-tube LHTES was optimized regarding the air temperature at the exit of LHTES during the day and the peak shift of heat supply. The results showed that optimal mass of PCM in LHTES is 150–200 kg/m^2 and the optimal air flow-rate is 40 m^3/h per m^2 of the SC aperture area. The analysis of the system performance at different levels of daily solar irradiation has shown that 54–67% of the heat produced by solar air heating system in daytime can be delivered during the night time for building heating.

Keywords: Latent heat storage; Phase change material; Vacuum tube air solar collector; Solar heating

1. Introduction

A significant part of the final energy in buildings is consumed to provide adequate living comfort. In the EU, this share is close to 40%. The revised Energy Performance of Buildings Directive 2010/317EU foresees that after 2020 almost exclusively nearly zero energy buildings (nZEB) will be built, as a result of European climate and energy policy. Energy in nZEB has to be largely provided by renewable energy sources (RES), as energy produced on the building envelope or its vicinity. Regarding heat and cold supply, solar thermal systems and free cooling systems could have a significant role in nZEB. An important element of these systems is heat storage, as it reduces the time mismatch between the availability of energy source and the actual energy need for heating and cooling.

In recent years, a great deal of research of latent heat thermal energy storages (LHTES) in systems for free cooling of buildings has been conducted (Waqas and Ud Din, 2013). These systems utilize the coolness of ambient air during the night to cool the building during the day. Studies have shown that these systems can be very effective in reducing energy use for cooling (Takeda et al., 2004; Arkar and Medved, 2007). In energy efficient buildings built for the American Solar Decathlon competition (Rodriguez-Ubinas et al., 2012), the use of PCM and LHTES predominates in attempts to improve the energy performance of the buildings. From the presented cases, it can be identified that in these buildings different PCMs were used for both the heating and the cooling of a building. As shown by Medved and Arkar (2008), the optimum

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Nomenclature

A	cross-section (m^2)
A_{ap}	aperture area of SC (m^2)
Bi	Biot number (–)
c_1	heat loss coefficient (W/(m^2 K))
c_2	temperature dependence of the heat loss coefficient (W/(m^2 K^2))
c_3	wind speed dependence of the heat loss coefficient (J/(m^3 K))
c_4	long-wave irradiance dependence of the heat loss coefficient (W/(m^2 K))
c_5	effective thermal capacity (J/(m^2 K))
c_6	wind speed dependence of the zero loss efficiency (s/m)
c_{eff}	effective heat capacity (J/(kg K))
COP	coefficient of performance (–)
c_p	specific heat (J/(kg K))
D	tube diameter (m)
E	electric energy (J)
E_L	long-wave irradiance (W/m^2)
F'	efficiency factor of SC (–)
G	global solar radiation on SC plane (W/m^2)
h	heat transfer coefficient (W/(m^2 K))
H	daily solar irradiation (kW h/(m^2 day))
k	thermal conductivity (W/(m K))
K_θ	incidence angle modifier (–)
L	latent heat of melting or solidification (J/kg), LHTES length (m)
m	mass (kg)
$\dot{m}$	mass flow-rate (kg/s)
m'_{pcm}	mass of PCM per SC area (kg/m^2)
P	perimeter (m)
Q	delivered heat (J)
q	share of delivered heat (–)
$\dot{Q}$	useful power from SC, heat flux (W)
r	radial coordinate (m)
T	temperature (°C)
t	time (s)
u	surrounding wind speed (m/s)
U	thermal transmittance (W/(m^2 K))
$\dot{V}$	air volume flow-rate (m^3/h)
x	axial coordinate (m)

Greek symbols

θ	incidence angle (°)
θ'	heating or cooling rate (K/s)
η	instantaneous efficiency (–)
η_0	zero loss SC efficiency (–)
ϕ	daily utilizability factor (%)
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant (W/(m^2 K^4))
$(\tau{\cdot}\alpha)_{en}$	effective transmittance–absorptance product at normal incidence (–)

Subscripts, superscripts

a	ambient
b	beam
cs	clear sky
d	diffuse
eff	effective
exp	experimental
hs	heat storage
i	inlet, inner
in	indoor
m	mean
$night$	night time
num	numerical
o	outlet, outer
p	peak
pcm	phase change material
pos	partly overcast sky
s	solid
sc	solar collector
ti	thermal insulation

PCM melting temperature in LHTES for free cooling in places with Continental and Mediterranean climate is between 22 °C and 28 °C, and this may also be suitable for LHTES in solar heating systems. Furthermore, in some other free cooling studies (Takeda et al., 2004; Zalba et al., 2004; Lazaro et al., 2009; Dolado et al., 2011; Raj and Velraj, 2011), the use of PCM with melting temperatures higher than 22 °C can be found. As the operation time of a free-cooling system is limited to the summer time, the cost effectiveness of its main element (i.e. latent heat storage) could be improved if this element is integrated into a heating system, for example in a solar air heating system. Using LHTES for both the heating and cooling of the building significantly improves the economics of free-cooling and solar air heating systems.

Alkilani et al. (2011) recently presented an overview of heating systems, containing air SC and heat storage. They showed that, in addition to systems for drying crops and greenhouse heating, there are many applications for heating of the buildings. They also determined that research and applications with LHTES have been prevalent in the recent period. Saman et al. (2005) presented and analysed the performance of the building heating system with roof-integrated SC and LHTES with plates of PCM. They analysed the PCM with a melting point of 28 °C. They analysed the influence of different but constant inlet air