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Energy conservative air conditioning system using silver nano-based PCM thermal storage for modern buildings

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ABSTRACT

This work aims at improving the thermal performance and energy efficiency of chilled water based variable air volume air conditioning system integrated with the silver nanoparticles embedded latent thermal energy storage system. The latent thermal energy storage air conditioning system incorporated with the demand controlled ventilation and the economizer cycle ventilation schemes were experimentally investigated for the year-round building air conditioning application. Phase change material embedded with silver nanoparticles enabled it to exhibit improved heat transfer mechanisms in charging and discharging cycles. Experimental results suggest that the proposed air conditioning system achieved an on-peak and per day average energy savings potential of 36–58% and 24–51%, respectively, for year round operation while compared to the conventional air conditioning system. Similarly, while compared with a basically similar variable air volume air conditioning system, the proposed air conditioning system yielded 7.5–18.6% and 7.9–17.8% of on-peak and per day average energy conservative potential, respectively. Furthermore, test results infer that the combined effects produced by the silver nanoparticles embedded latent thermal energy storage system with the ventilation techniques augmented the overall thermal performance of the system. In total, the combined air conditioning system would be beneficial in terms of accomplishing good thermal comfort, acceptable indoor air quality and energy redistribution needs in buildings without sacrificing energy efficiency.

1. Introduction

Energy production and consumption plays a vital role in determining the energy conservation at every step of the economic development of a country. In recent years, the increased demands in the constructional sector have led to the development of elegant and huge building structures worldwide. It is interesting to note that, buildings would consume one-quarter to one-third of the overall energy generated globally. In order to sustain the living standards in buildings, continuous value-added engineering design and incorporation of the energy efficient heating, ventilation and air conditioning (HVAC) systems are greatly necessitated.

Many research contributions addressing the issues related to consumption of global and total energy, carbon dioxide (CO_2) emissions, indoor thermal comfort were reported [1–4]. Table 1 presents an outlook of the global annual primary energy consumption estimated for building sector. The possible ways to reduce the effects caused by these issues and to improve energy efficiency in buildings have been suggested. Employing advanced intelligent logical control mechanisms into the integrated building management systems would enable the modern HVAC systems to perform better than the conventional systems [5,6].

In recent times, interesting research works have been executed for achieving good indoor thermal comfort conditions to occupants [7–9]. Indoor temperature setting related issues were addressed and possible ways to improve building energy efficiency have been suggested. Although there are several measures available to minimize the net energy consumption in buildings, there is still a need for an efficient system which can offset on-peak thermal load demand with better energy savings potential. In this perspective, thermal energy storage systems are primarily intended for enhancing the performance of thermal systems and to store and release heat energy on short-term or diurnal or seasonal basis depending on the thermal load requirements experienced in buildings.

One such application is where incorporation of thermal energy storage systems in buildings has revealed potential benefits in terms of storing and releasing heat energy based on fluctuated load demand at lower overall energy usage [10–12]. Approximately

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Nomenclature

A	area (m^2)
C	specific heat (kJ/kg K)
C_d	coefficient of discharge (–)
D	depth of damper (m)
F_o	Fourier number (–)
g	volumetric heat generation (W/m^3)
k	thermal conductivity (W/m K)
P	pressure (bar)
Q	heat transfer (kW)
q	volumetric flow rate (m^3/s)
R	radius of spherical capsule (m)
s	dimensionless position of the solid–liquid interface (-)
Ste	Stefan number (–)
T	temperature (K)
t	time (s)
U	overall heat transfer coefficient (W/m^2 K)
W	width of damper (m).

Greek symbols

β	dimensionless heat generation parameter (–)
θ	damper angle (degrees)
ρ	density (kg/m^3).

Subscripts

a	air
ai	indoor air
cl	ceiling
dp	damper
f	fusion
fl	floor
g	glazing
i	infiltration
in	inlet
L	liquid phase
mel	complete melting
np	nanoparticles
o	external fluid
oa	outdoor air
ou	outlet
pl	cooling plant
S	solid phase
sl	solar
w	wall
wi	inner wall
wo	outer wall.

List of abbreviations

A/C	air conditioning
AgNP	silver nanoparticles
CAV	constant air volume
CCU	centralized controlled unit
DCV	demand controlled ventilation
ECV	Economizer cycle ventilation
ETS	energy transfer station
GHG	green house gas
HTF	heat transfer fluid
HVAC	heating, ventilation and air conditioning
IAQ	indoor air quality
PCM	phase change material
PSA	particle size analyzer
SAT	supply air temperature
NTES	silver nanoparticles embedded latent thermal energy storage
TEM	transmission electron microscope
VAV	variable air volume.

50% of per day total cooling load can be catered with ice-cool thermal energy storage system being incorporated with the base load chillers installed in buildings [13].

Dorgan and Ellison [14] put forth detailed design procedures for cool thermal storage system. Based on the guidelines outlined cool thermal energy storage systems can be designed for efficient use and could be implemented for practical building cooling applications. Performance improvement of cool thermal energy storage systems in relation with the building energy efficiency have been established through the extensive modeling and simulation techniques. Some of these systems were also field tested and implemented in buildings located in hot and arid climatic conditions [15–21]. As a result, these systems have contributed for reduction in on-peak power and energy demand in such buildings by approximately 31% and 36%, respectively.

Energy redistribution requirements can be effectively met by using thermal energy storage (TES) systems integrated with the dedicated HVAC systems in buildings. Phase change materials (PCMs) contained in the TES systems are a class of materials which exhibits relatively good latent heat of fusion while subjected to medium of heat transfer (e.g., air/water/brine solutions). In this context, research studies investigating variable geometries, thermal configurations, dynamic modeling, heat transfer characteristics and stability of different PCMs dedicated for cooling and heating applications in buildings as well as to improve energy efficiency have been reported in recent years [22–33].

More interestingly, PCMs impregnated or encapsulated with nanoparticles having higher surface to volume ratio exhibits much improved thermophysical properties than in its pure state. Khodadadi and Hosseinizadeh [34] developed suitable numerical models and investigated the freezing and melting characteristics of PCM containing dispersed nanoparticles using computational domain. The high energy discharge rate of nanoencapsulated PCM observed made it as a potential candidate for TES applications.

Fang et al. [35] prepared nanoencapsulated PCM with polystyrene as shell and n-octadecane as the core using ultrasonic-based in-situ polymerization technique. Polymerization factors augmented the heat capacity of this PCM and improved the thermal stability and viscous effects as well. Similar studies dealing with different nanoencapsulation techniques with dispersed nanoparticles have been performed in order to exhibit good melting and freezing characteristics of PCMs [36,37]. Compared to the regular studies done on the melting characteristics of PCM, Sanusi et al. [38] performed a different approach to investigate the thermal performance of PCM during solidification process with the use of graphite nanofibers as thermal conductivity enhancers.

Table 1
Estimated global annual primary energy consumption by buildings [3].

Year	Energy consumption (EJ/year)
2004	76.2
2010	86.7
2015	95.7
2020	102.7
2025	108.9
2030	115.7