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Numerical analysis of a shell-and-tube latent heat storage unit with fins for air-conditioning application

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HIGHLIGHTS

- Shell-and-tube thermal storage with two different HTFs studied for A/C application.
- Staged heat transfer model developed for varying natural convection effects in PCM.
- Studied impacts of HTF flow rate, inlet temperature, and fin height on performance.

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ABSTRACT

Free cooling is an effective way to make good use of night cold energy and helps to reduce air-conditioning energy consumption in the daytime. This research proposed integrating a new-type of shell-and-tube based phase change material (PCM) thermal storage system with conventional air-conditioner to increase cooling coefficient of performance (COP). The proposed PCM thermal storage unit uses two different kinds of media (water and air) for the heat transfer fluids (HTF). Water is used for charging loop while air is used for discharging loop. The two HTFs better fit the heat transfer needs of nighttime's free cooling harvest and daytime's condensing water use by the air-conditioning system. A numerical model for the PCM thermal storage unit has been developed, particularly with consideration of staged natural convection effects in PCM melting process. The numerical model equipped with a new PCM staged effective thermal conductivity has been validated by experimental data. Numerical study has evaluated the effects of HTF inlet temperature, mass flow rate and conductive fin height on the PCM thermal storage system's performance. Modeling results show that HTF mass flow rate and fin height need to be designed through an optimization process according to the cooling load profile and achieve best performance of the PCM thermal storage system. Effectiveness of this proposed PCM thermal storage system is generally higher than 0.5. Case study of replacing conventional cooling tower by the proposed PCM thermal storage system for a water-cooled air-conditioner shows a COP value increase of about 25.6%.

1. Introduction

Night ventilation, one type of free cooling methods, is the use of low temperature night air to directly cool down the structure of a building. It is a useful and low-cost approach to improve indoor thermal comfort and reduce the daytime cooling load of air-conditioners in summer if there is a large diurnal temperature shifts (e.g. 12–15 °C [1] or greater). However, traditional night ventilation is not satisfactory enough due to the low thermal capacity of the building envelope. An alternative improved method is to incorporate night ventilation with latent heat thermal energy storage system (LHTESS) [2]: use LHTESS to store cool energy at night and release for using during the daytime. LHTESS could provide much higher cold storage density, with a small temperature difference between energy charging and discharging processes.

There are good reviews on PCM-based cooling for building applications [1,3–4]. Osterman et al. [3] summarized the PCM based cooling technologies for buildings, including free cooling applications, cold storage air-conditioning system with capsules packed bed (e.g., ice storage), ventilation cooling system based on PCM, and PCM based envelopes. Waqas and Din [1] presented a review on PCM storage for free cooling of buildings. Pomianowski et al. [4] reviewed thermal energy storage technologies based on PCM application in buildings such as PCM in construction materials (passive/active), PCM in glazing, shadings, blinds, and PCM in HVAC components/heat exchangers. However, existing integration of PCM with air-conditioning system either uses water as the phase

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Nomenclature

c	constant in Eq. (13)
COP	coefficient of performance
C_p	specific heat, J/kg K
f	PCM liquid fraction
g	gravitational acceleration, 9.81 m/s^2
h	PCM volumetric sensible enthalpy, J/m^3
H	PCM volumetric total enthalpy, J/m^3
HTF	heat transfer fluid
k	thermal conductivity, W/m K
l	height, m
L	dimensionless height
m	mass, kg
M	number of grid in r direction
n	constant in Eq. (13)
N	number of grid in x direction
PCM	phase change material
q	energy change rate in one cell, W
Q	total energy charging rate of PCM, W
r	radius coordinate, m
R_1	inner radius of the inner tube, m
R_2	outer radius of the inner tube, m
R_3	inner radius of the outer tube, m
R_4	outer radius of the outer tube, m
Ra	Rayleigh number
t	time, s
T	temperature, °C
u	velocity, m/s
U	convective heat transfer coefficient, W/m^2 K
x	axial coordinate, m
x_e	dimensionless axial coordinate, $\frac{x}{\mathrm{Re\,Pr}}$

Greek symbols

α	thermal diffusivity, m^2/s
ΔH	latent heat of fusion, J/kg
μ	dynamic viscosity, kg/m s
ρ	density, kg/m^3
β	thermal expansion, 1/K

Subscripts

0	reference
a	air
act	actual
avg	average
e	effective
eva	evaporative
f	water
fin	fin
init	initial
l	liquid
m	melting
p	phase change material (PCM)
s	solid
th	theoretical
w	tube wall

change material or is for a loose coupling such as ventilation focused. Kang et al. [5] introduced night ventilation with PCM packed bed storage (NVP) system for bulding application. Antony Aroul Raj and Velraj [6] developed a PCM-heat exchanger module for free cooling. Amongst these researches, PCM (one type of LHTESS) free cooling applications dominantly used air as heat transfer fluid (HTF) in both charging and discharging processes as they were focused on ventilation. Therefore, the cool energy stored in PCM at night is directly discharged into the building through indoor air circulation at daytime. However, for the most intensely analysed LHTESS, shell-and-tube type [7–9], which accounts for more than 70% according to a survey of the previously published LHTESS relevant papers [10], water is generally used as HTF since water provides more effective heat transfer than air. In this research, to integrate PCM thermal storage with conventional air-conditioner, air and water have been used as HTF for night time heat discharging process and daytime heat charging process, respectively. The PCM thermal storage will act as air-conditioner's heat sink, which will help reduce the condenser side temperature and thus increase air-conditioner's COP.

One of the challenges PCM research faces is the phase change material's low thermal conductivity. Several techniques have been introduced to improve heat transfer in PCM thermal storage system such as integrating with fins and extended surfaces [11–13], embedded in porous metals [14,15], composing high thermal conducting material [16], using heat pipes [17] and multiple PCMs [18]. For shell-and-tube latent thermal storage system, integrating with fins appears a very attractive option from both economic and practical considerations. The applications of this particular technique can be found in waste heat recovery [19], solar power plants [11] and solar cooling and refrigeration [20].

Leo Samuel et al. [21] reported that conventional mechanical air conditioning systems are energy intensive and increase the electric grid system's burden in summer peak hours. Research shows that for air-cooled air-conditioner, if the on-coil temperature of the condenser is raised by 1 °C, the COP of the air-conditioner drops by around 3% [22]. Therefore reducing air-conditioner condenser's operational temperature will be highly beneficial for the air-conditioner's performance efficiency, which has attracted great efforts from researchers, such as using new types of refrigerant [23], optimizing placement of the condenser [22], investigating the effect of temperature stack [24] and roof reflectance [25], and adopting water-cooled condensers [26]. Water-cooled condensers are in general more energy efficient than air-cooled condensers. Chen et al. [27] gave the experimental results that the COP of the water-cooled air-conditioner is, on average, 17.4% higher than that of the air-cooled air-conditioner. Woolley et al. [28] and Harrington and Modera [29] investigated using swimming pools as heat sinks for air conditioners and concluded that rejecting heat to an outdoor swimming pool can save approximately 25–30% of single-family residential cooling electric use as compared to using the same compressor but rejecting the heat to ambient air. However, since the on-coil water temperature of the water-cooled air-conditioner cannot drop down to below outdoor air wet-bulb temperature, the energy efficiency improvement is limited.

Asrael et al. [30] performed a feasibility study of lowering the water-cooled condenser's inlet water temperature using thermal water storage. The thermal water storage introduced was used to store the cooled water from cooling tower at night and then used during daytime on-peak hours. Results suggested that on-peak power use can be saved as much as 35%. However, compared to sensible heat storage, latent heat storage has much larger storage capacity but requires smaller installation space. In addition, thermal water storage (as well as cooling tower) may also intensify water crisis in draught regions.

This research incorporated active mechanical cooling and passive free cooling approaches using a shell-and-tube PCM thermal storage system. This system has advantages of energy efficiency