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Thermal performance optimization of free cooling systems using enhanced latent heat thermal storage unit

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HIGHLIGHTS

- The performance is investigated of LHTS free cooling system employing multiple PCMs.
- The phase change process is predicted using the effective heat capacity method.
- The energy effectiveness method is employed to optimize the LHTS unit.
- Energy based optimization is performed to determine the COP of the free cooling system.
- The two methods are compared to find the most appropriate for optimization.

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ABSTRACT

Free cooling systems use phase change materials (PCMs) to store outdoor cold during the night and to supply it to the indoor environment during the day when the need for cooling increases. This work presents a numerical investigation of the performance enhancement of a free cooling system using a latent heat thermal storage (LHTS) unit employing multiple PCMs. The PCM storage system consists of several flat PCM slabs arranged in layers with a passage in between for the heat transfer fluid (HTF). Using the effective heat capacity method, the process of melting and solidification of the PCM is predicted. The energy storage effectiveness (as a new performance parameter for LHTS units) and coefficient of performance (COP) of the system are calculated. These two performance indicators are used to optimize the system. The suitability of both methods for optimization purpose is discussed indicating the superiority of the energy based (COP) method.

1. Introduction

Cooling demand has been increasing due to the developing comfort expectations and technological developments around the world. Air conditioning systems are responsible for a large amount of the total energy consumption in buildings. Recently, thermal energy storage (TES) systems, especially latent heat thermal storage (LHTS) units, have been introduced as a good solution to eliminate the mismatch between energy supply and energy demand. TES units have gained greater attention from the view point of global environmental problems and applications in various engineering fields. LHTS in general, and phase change material (PCM) storage in particular, have been investigated for over 20 years and are described in various references. Important LHTS applications and advances in LHTS materials and related heat transfer have recently been reviewed [1–4].

Due to the advantages offered by LHTS such as low temperature variation during melting and solidification cycles and high TES capacity, PCMs have been utilized in numerous applications specially in solar heating and cooling [5–7] and in conventional air conditioning [8–10]. Esen and Ayhan [11] theoretically investigated the performance of solar assisted TES, showing that in order to optimize the LHTS, the PCM, the mass flow rate and the inlet temperature of the heat transfer fluid (HTF) are important parameters. Also, Esen [12] studied experimentally and theoretically a TES linked to a solar powered heat pump system.

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Nomenclature

c	specific heat (J/kg K)
E	energy storage effectiveness
E^*	modified energy storage effectiveness
k	thermal conductivity (W/m K)
L	latent heat of fusion (J/kg)
l	length of storage (m)
p	pressure (Pa)
P	total energy consumption (kW h)
$\dot{Q}$	heat rate (W)
Q	heat (J)
r	compactness factor
T	temperature (°C)
t	time (s)
$\dot{V}$	volumetric flow rate (m^3/s)
$\dot{W}$	power (W)

Greek symbols

δ	thickness of PCM slab (m)
ε	heat exchanger effectiveness
$\bar{\varepsilon}$	average effectiveness
ε^*	modified effectiveness
γ	thickness of HTF channel (m)
η	efficiency

Subscripts

acc	accumulated
m	melting
s	solidification

Zalba et al. [13] experimentally studied a free cooling system using a PCM. They designed and constructed an installation able to measure flow and temperature of the inlet and outlet air of the storage. Experiments were carried out with a design of experiment (DOE) strategy that allowed an empirical model to be proposed for the factor studied. The results showed that the thickness of the PCM encapsulate, the inlet temperature and the air flow significantly influence the melting and solidification process. Lazaro et al. [14] presented novel design conclusions based on an empirical model for an actual-scale prototype of a PCM-air heat exchanger. They concluded that to maintain a specific temperature when the cooling demand is high, the PCM phase change temperature should be lower. On the other hand, for very low cooling demands, the phase change temperature should be close to the required temperature level.

Due to the relatively low thermal conductivity of PCMs, many investigations have been performed to improve the heat transfer in LHTS. Some of the various techniques adopted for enhancing the thermal performance of the LHTS units follow:

- The dispersion of high conductivity particles in the PCM [15,16]
- Using a high thermal conductivity porous matrix [17,18]
- The addition of fins to the external surface of the storage [19,20]
- Employing multiple families of PCMs in the unit

Multiple PCM units are LHTS units employing more than one PCM to store and release thermal energy. Shaikh and Lafdi [21] investigated the impact of using different configurations of multiple PCM slabs arrangements. The results indicate that the total energy storage rate can be significantly enhanced by using composite PCMs as compared to a single PCM. A model for prediction of the thermal performance of a multi-layer PCM storage unit was presented by Brousseau and Lacroix [22]. They performed parametric studies to assess the effect of various design and operating conditions on correlations for the total energy stored and the average output heat load. Wang et al. [23] presented a theoretical investigation and numerical analysis for multiple PCM slabs to enhance the charge and discharge rates of TES systems. They noted that the phase change time of composite PCMs with optimum linear phase change temperature distributions can be decreased by as much as 25–40%. Cui et al. [24] recently proposed a numerical model for a solar receiver thermal storage module using three PCMs. They pointed out that the multiple PCM system can be advantageous to enhance the energy storage rate and reduce the fluctuation of the working fluid exit temperature of the receiver device. Kurnia et al. [25] carried out a numerical investigation to enhance the heat transfer performance of TES system by geometric modification and use of multiple layers of PCM. They found that the arrangement of PCMs significantly affects the heat transfer performance: placement of a high melting point PCM at the inlet side during melting improves heat transfer.

A diagram of a free cooling system using a LHTS unit is shown in Fig. 1. The LHTS unit consists of several layers of PCM slabs placed parallel to each other and air as heat transfer fluid flows through the channels. Each slab contains multiple PCMs in a plastic container. Recently an indirect evaporative cooler has been introduced by Esfandiari Nia [26], the space between the air channels of this cooler will be filled with the PCM material. The specifications of the geometry of this system are the same as mentioned for the evaporative cooler.

In the present work, the melting and solidification processes of the PCM and heat transfer in the HTF are studied numerically in two-dimensions using the effective heat capacity method [27,28]. Recently a new performance parameter for LHTS units called the energy storage effectiveness has been introduced by Tay et al. [29]. The paper presents an optimization based on the energy storage effectiveness as the performance indicator of PCM systems. Also, the energy based optimization recently proposed by the authors [28] is performed to determine the coefficient of performance (COP). A comparison between energy storage effectiveness and energy based optimization methods is performed to find the most appropriate method of optimization.

2. Model description

The performance of a LHTS unit mainly depends on the difference between the temperature of the air (as HTF) and the PCM melting temperature. In multiple PCM units, PCMs can be arranged in decreasing order of their melting temperatures in the case of melting processes and in increasing order of their melting temperatures in the case of solidification processes. Such units are

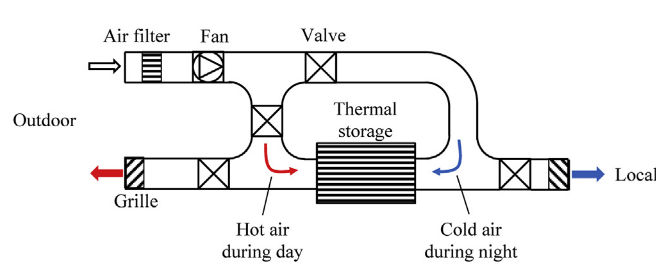

Fig. 1. Installation of thermal storage for free cooling.