Energy Conversion and Management 67 (2013) 1–7

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Thermal performance of a multiple PCM thermal storage unit for free cooling

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ARTICLE INFO

Article history:
Received 16 July 2012
Received in revised form 2 October 2012
Accepted 30 October 2012
Available online 7 December 2012

Keywords:
Thermal energy storage (TES)
Phase change material (PCM)
Latent heat thermal storage (LHTS)
Free cooling
Effective heat capacity

ABSTRACT

As demand for refrigeration and air conditioning increased during the last decade, the opportunities have expanded for using thermal energy storage (TES) systems in an economically advantageous manner in place of conventional cooling plants. Many cool storage systems use phase change materials (PCMs) and achieve peak load shifting in buildings. This work presents numerical investigations of the performance enhancement of a free cooling system using a TES unit employing multiple PCMs. The TES unit is composed of a number of rectangular channels for the flowing heat transfer fluid, separated by PCM slabs. Using the effective heat capacity method, the melting and solidification of the PCM is solved. The forced convective heat transfer inside the channels is analyzed by solving the energy equation, which is coupled with the heat conduction equation in the container wall. The effect of design parameters such as PCM slab length, thickness and fluid passage gap on the storage performance is also investigated using an energy based optimization. The results show that a system which can guarantee comfort conditions for the climate of Tabriz, Iran has an optimum COP of 7.0. This could be achieved by a combination of $CaCl_2{\cdot}6H_2O$ with RT25 with the optimum air channel thickness of 3.2 mm, length of 1.3 m and PCM slab thickness of 10 mm.

1. Introduction

Electrical energy consumption varies significantly during the day and night according to the demand by the industrial, commercial, residential sector and other activities. In hot and cold climate countries, a major part of the load variation is due to loads for air conditioning and space heating respectively. Cooling demand has been increasing due to the developing comfort expectations and technological developments around the world. Climate change has brought additional challenges for cooling systems designers. Significant economic benefits can be achieved by using thermal energy storage (TES) for heating and cooling in residential and commercial buildings. These demands can be satisfied by smoothing the temporal variations with the help of latent heat thermal storage (LHTS) systems. 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 heat transfer have recently been reviewed [1–8].

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 including solar heating and cooling [9–11], conventional air conditioning [12–14], below-floor heating [15] and building envelopes [16–20].

Saman et al. [21] employed a two-dimensional numerical model based on an enthalpy formulation and analyzed the thermal performance of a flat thermal storage unit. The outlet air temperatures and heat transfer rates predicted by this model were compared with experimental data, and showed close agreement. Halawa et al. [22] developed a one-dimensional model to study the heat transfer in the thermal storage unit with the same arrangement as Saman et al. [21]. They proposed a phase change processor algorithm to solve the phase change of the PCM in melting and solidification processes and also to determine the liquid fraction of the PCM node. The model has been verified with experimental results with air as the heat transfer fluid (HTF). Due to the small thickness and the high length to thickness ratio of the slabs under investigation, they used a one dimensional model for quick computation time. Lazaro et al. [23,24] presented an experimental set up for testing PCM–air real-scale heat exchangers. The results showed that a heat exchanger using a PCM with lower thermal conductivity and lower total stored energy, but adequately designed, has higher cooling power and can be applied for free cooling. The free cooling potential of using PCMs in buildings in various climate conditions was studied by Takeda et al. [25] and Medved and Arkar

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http://dx.doi.org/10.1016/j.enconman.2012.10.018

Nomenclature

A	cross sectional area, m^2
a	thickness of PCM slab, m
b	thickness of air channel, m
c	specific heat, $J\,kg^{-1}\,K^{-1}$
D_h	hydraulic diameter, m
h	convective heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
L	latent heat of fusion, $J\,kg^{-1}$
l	length of storage, m
Nu	Nusselt number = hD_h/k_f
p	pressure, Pa
P	total energy consumption, kW h
q''	heat flux, $W\,m^{-2}$
$\dot{Q}$	heat rate, W
Re	Reynolds number
S	location of solid–liquid interface, m
T	temperature, °C
t	time, s
u	velocity, $m\,s^{-1}$
$\dot{V}$	volumetric flow rate, $m^3\,h^{-1}$
$\dot{W}$	power, W
x, y	spatial coordinates, m

Greek symbols

η	efficiency
ρ	density, $kg\,m^{-3}$

Subscripts

1	begin melting
2	end melting
b	bulk
i	initial
f	HTF
l	liquid
m	melting
s	solid
w	wall

[26]. Both studies indicated that the potential of free cooling mainly depends on the amplitude of the ambient air temperature variations.

In spite of various advantages of PCMs, LHTS systems possess a major disadvantage: low melting and solidification rates owing to the low thermal conductivity of the PCM. To overcome this disadvantage a number of studies have been carried out to enhance the performance of LHTS systems. The various techniques adopted for enhancing the thermal performance of the LHTS units include the dispersion of high conductivity particles in the PCM [27], using a high thermal conductivity porous matrix [28], the addition of fins to the external surface of the HTF passage [29–31], and employing multiple families of PCMs in the unit [32,33].

Multiple PCM units are those LHTS systems employing more than one PCM to store or release thermal energy. The heat transfer rate in a LHTS system and thus the performance of the system during melting and solidification mainly depend on the difference between the HTF temperature and the PCM melting point. If a single PCM is used in the system, then this temperature difference would decrease in the flow direction of the HTF. This results in a decrease in heat transfer rate and thus poor performance of the system. If multiple PCMs with different melting temperatures are packed in the system in decreasing order of their melting points, then nearly a constant temperature difference can be maintained during the melting process, even though the HTF temperature decreases in the flow direction. This leads to an almost constant heat flux to the PCM. During solidification, if the HTF flow direction is reversed, the PCMs remain in increasing order of their melting points. Once again a nearly constant heat flux from the PCM to the HTF is possible. Farid and Kanzawa [34] employed three PCMs of different melting points in a LHTS. Air was used as the HTF. The results showed about 10% increment in heat transfer rate during both charging and discharging relative to a single PCM. Xiang Gong and Mujumdar [35] developed a finite element phase change heat conduction model for cyclic melting/solidification in composite phase change material slabs. Numerical experiments demonstrated that the melting/solidification rates could be greatly enhanced by using composite PCMs with different melting points compared with using a single PCM in a slab.

The purpose of the present study is to perform an energy based optimization of free cooling systems using multiple PCM LHTS units. Recently an indirect evaporative cooler, called a static dew point cooler, has been introduced by Esfandiari Nia [36]. This heat exchanger is manufactured from plastic material plates. Air (the HTF) flows through a large number of small parallel channels. The idea is to fill the space between the air channels with the PCM material. This paper presents a two-dimensional numerical analysis for the system illustrated in Fig. 1. The system consists of several layers of PCM slabs placed parallel to each other. Each slab contains multiple PCMs. By selecting the PCMs with appropriate melting points, the system can be used for free cooling applications. The effective heat capacity method is used as the numerical model [37] and is applied to determine the effects of design parameters on system performance. The theoretical analyses are based on the finite element method.

2. Mathematical formulation

The solidification and melting processes of the PCM and heat transfer in the HTF are unsteady two-dimensional problems for the system studied. Due to the negligible variation of the container wall temperature, temperature variations normal to the flow direction are ignored [13,38]. To develop a mathematical model, it is assumed that the effect of natural convection is negligible. As observed by Laouadi and Lacroix [39] for a PCM storage geometry similar to that in the present study, the effect of natural convection is significant only when the PCM slabs are in the vertical position and heated from the side. Further assumptions are that the thermophysical properties of PCMs are independent of temperature, but different for solid and liquid phases [21,22].

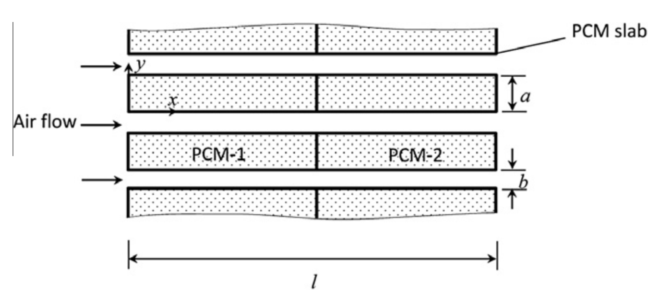

Fig. 1. Schematic diagram of the TES unit.