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Experimental investigation and performance analysis of a fin tube phase change cold storage unit for high temperature cooling application

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ABSTRACT

A fin tube phase change cold storage unit based upon self-developed C–L acid (capric and lauric acid) PCM with the phase change temperature of 14.97 °C for high temperature cooling application was designed. The charging performance of the cold storage unit was experimentally investigated. Moreover, the performance analysis based upon the charging performance was conducted for the purpose of optimizing the structural parameters. It is shown that the whole charging process of the optimized scheme is faster than that of the experimental unit by 26.3%. In practical applications, two or more such fin tube phase change cold storage units in parallel can be used to meet different cold storage demand of high temperature cooling systems in buildings.

1. Introduction

Due to the increasing demand of refrigeration, a key point in the future will be to develop more efficient cold generation as well as cold storage technologies [1]. As a feasible scheme, high temperature cooling application in buildings has been received more and more attention as it shows an advantage of comfort and high efficiency. The goal to improve the efficiency of cooling systems can be achieved by raising the evaporating temperature of refrigeration units. In this respect, solar cooling systems and radiant cooling systems are typical examples. Some previous researches showed that, the outlet water temperature from a solar absorption chiller was usually 12–14 °C. (An absorption chiller usually produces chilled water with the temperature of 7 °C. However, the coefficient of performance for existing solar absorption cooling systems is not high. So, in many such projects, the chilled water temperature were raised to 12–14 °C in order to improve the coefficient of performance of absorption chillers.) [2,3]; the inlet water temperature of a radiant cooling terminal was usually designed as 16–18 °C [4–6]. However, a solar cooling system is usually unstable due to the intermittent energy reception from the sun. In addition, as solar energy is a periodic energy source, there exists a problem of mismatch between cooling generation and cooling demand in buildings [7]. Thanks to the high energy storage density of phase change material (PCM), the storage systems with PCM are capable of improving solar cooling systems and eliminating the mismatch problem [8]. As for a radiant cooling system, the problem of moisture condensation below dew point temperature has also hindered its widespread utilization [9]. The use of PCM in radiant cooling systems can in some degree defer or wipe off the moisture condensation phenomenon. What's more, PCM slabs or in other forms incorporated in radiant cooling systems have the benefit of providing the necessary thermal inertia for a lightweight building with less mass and structural loads [10].

Phase change materials, which mainly store energy by latent heat, have many advantages over materials that can only store energy by sensible heat, a high storage density and isothermal behavior during freezing/melting process being the two notable ones [11]. Nevertheless, most of phase change materials present the drawback of having a low thermal conductivity. Therefore, two main research topics have been carried out to improve the thermal performance of PCM. For one thing, composite phase change materials with addition of foreign substances have been investigated to provide a desired phase change temperature and to enhance energy efficiency [1,12,13]. Besides, Tang et al. [14] reported the preparation and thermal properties of the stearic acid/TiO_2 composites as phase change materials for building thermal energy storage. It was shown that the composites had a good thermal stability, and could be used as shape-stabilized phase change materials for building thermal energy storage. Zhou et al. [15] valuated the thermal

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Nomenclature

c	specific heat capacity (kJ kg^{-1} K^{-1})
h	specific enthalpy (kJ kg^{-1})
H	height of the calculating element (m)
m	flow rate (kg s^{-1})
q	charging rate (W)
Q	charging capacity (kJ)
r	radius (m)
R	radius of cold storage unit (m)
T	temperature (°C)
z	height (m)
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
τ	time (s)
φ	angle (°)
ΔT	temperature difference between inlet and outlet (°C)

Superscript

*	saturation state

Subscripts

0	initial condition
f	heat transfer fluid from homothermal circulator
i	inner
l	liquid phase of PCM
p	phase transition of PCM
s	solid phase of PCM
w	external

performance of two phase change material composites, mixed type PCM-gypsum and shape stabilized PCM plates in a passive solar building. It was shown that the two PCM composites had superior behavior in stabilizing the room temperature. Memon et al. [16] developed a novel composite PCM having excellent heat transfer control in terms of thermal storage, thermal stability and reliability, physical and chemical compatibility by incorporation of lauryl alcohol into kaolin through vacuum impregnation. It was shown that the composite PCM was effective in reducing the indoor temperature and had the potential to minimize over heating the building. It could therefore be concluded that the prepared composite was a promising candidate for thermal energy storage in buildings. For another, the related research work has been focused on encapsulated PCM solutions with a large heat transfer area and a small thermal diffusion distance with PCM. In this respect, the research on optimization of heat exchangers with PCM may be an effective approach. Trp et al. [17] studied a shell and tube cold storage tank. Based on enthalpy formulation, the solid–liquid phase transition and heat conduction of the PCM were presented. The temperature distributions of the heat transfer fluid (HTF), PCM and tube wall were obtained under various working conditions and geometric parameters. Wu et al. [18] studied the dynamic discharging characteristics of a coil pipe cold storage tank using *n*-tetradecane as the PCM and aqueous ethylene glycol solution as the HTF. It was indicated that higher flow rate and higher inlet HTF temperature resulted in higher discharging rate, while the coil pipe diameter had little influence on the discharging characteristics. Cárdenas et al. [19] discussed the techniques to enhance heat transfer performance. A surface extension method of fins arranged orthogonally to the axis of the pipes was recommended. Besides, PCM embedded porous matrices was another technique discussed. It was indicated that the porosity of the matrix and its conductivity were the two main characters that influenced the performance. Al-Abidi et al. [20,21] investigated a triplex tube heat exchanger with internal and external fins. The numerical study was conducted on the relationships between structural parameters and the time for completion of melting of the PCM. It was shown that 8-cell PCM unit geometry consumed a shorter time in completing the melting of the PCM. Tay et al. [22] summarized some techniques for heat transfer enhancement in PCM thermal storages, which included finned tube systems and PCM embedded metal matrix structures like the carbon fiber and carbon brushes, as well as the shell and tube systems. Besides, a tube-in-tank phase change thermal energy storage system was proposed, in which a dynamic melting technique was used to improve the heat transfer during the melting process. The experimental test manifested a shorter time consumption for phase change process when dynamic melting technique was implemented.

Given the actual state of the art, the present work introduced a fin tube phase change cold storage unit for high temperature cooling application in buildings. The PCM used in this unit was a self-developed C–L acid (capric and lauric acid) PCM employing oleic acid as the additive which had been testified to be suitable for high temperature cooling application in our previous study [13]. The charging performance of the cold storage unit was experimentally investigated. Moreover, the performance analysis based upon the charging performance was conducted for the purpose of optimizing the structural parameters. In reference [13], we mainly described the thermal properties of the C–L acid (capric and lauric acid) PCM. However, in this paper, we proposed and optimized a fin tube phase change cold storage unit based upon this PCM. It is meaningful for the cold storage of high temperature cooling systems such as solar cooling and radiant cooling. In such systems, the cold storage with PCM is either used to eliminate the mismatch problem between cooling generation and cooling demand or to stabilize the working temperature. The cold storage unit presented in this paper can be utilized to realize the above goals. In practical applications in buildings, based upon the cooling load and design of air-conditioning systems, two or more such fin tube phase change cold storage units in parallel can be used to meet the cold storage demand of high temperature cooling systems with different cooling capacity.

2. Experimental set-up

2.1. Thermophysical properties of the PCM

A self-developed C–L acid (capric and lauric acid) PCM employing oleic acid as the additive was prepared to meet the demand of high temperature cooling systems. This PCM provides a suitable phase change temperature of 14.97 °C and a reasonable phase change latent heat of 115.1 kJ kg^{-1} [13]. The thermophysical properties of the PCM is shown in Table 1.

2.2. Experimental set-up of the fin tube phase change cold storage unit

A fin tube phase change cold storage unit was designed, as shown in Fig. 1. It is a 500 mm long cylinder with the diameter of 110 mm. A copper pipe with the diameter of 20 mm was placed along the central axis of the unit, which was used as the flow passage of heat transfer fluid. As for the inner space of the unit, 4 annular fins were firstly used to divide the inner space into 5 identical segments. And then, in each segment, 4 rectangular fins were orthogonally welded along the central tube, which divided the inner space of each segment into four identical portions. All the fins were made of copper with the thickness of 1 mm. Finally, the whole unit was filled with PCM. The outside surface of the unit