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A state-of-the-art review on hybrid heat pipe latent heat storage systems

M.S. Naghavi [a,*], K.S. Ong [b], M. Mehrali [a], I.A. Badruddin [a], H.S.C. Metselaar [a,*]

[a] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur, Malaysia
[b] Department of Industrial Engineering, Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Kampar, Malaysia

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ABSTRACT

The main advantage of latent heat thermal energy storage systems is the capability to store a large quantity of thermal energy in an isothermal process by changing phase from solid to liquid, while the most important weakness of these systems is low thermal conductivity that leads to unsuitable charging/discharging rates. Heat pipes are used in many applications – as one of the most efficient heat exchanger devices – to amplify the charging/discharging processes rate and are used to transfer heat from a source to the storage or from the storage to a sink. This review presents and critically discusses previous investigations and analysis on the incorporation of heat pipe devices into latent heat thermal energy storage with heat pipe devices. This paper categorizes different applications and configurations such as low/high temperature solar, heat exchanger and cooling systems, analytical approaches and effective parameters on the performance of hybrid HP–LHTES systems.

1. Introduction

Thermal energy transport and conversion play a very significant role in more than 90% of energy technologies [1]. This has recently attracted increasing interest related to thermal applications such as space and water heating, waste heat utilization, cooling and air conditioning [2]. What appears to be going on today is the spread of a new generation of thermal energy systems with the ability to perform optimally at its defined scope of functionality by thermal energy transmission management among different heat transfer processes like absorption, consumption, storing, releasing and/or recovering. Today, the majority of researches about thermal energy transmission is closely connected to the utilization of renewable energy sources and/or the storage of thermal energy in the form of the latent heat.

The main advantage of latent heat thermal energy storage (LHTES) systems is the its capability to store a large quantity of thermal energy using an isothermal process by changing phase from solid to liquid. Many types of phase change materials (PCM) exist that have the potential to be considered as an LHTES. The required properties for PCMs are a melting point, according to the needs of the application, high heat of fusion, large thermal conductivity, and a small temperature difference between the melting point and solidification point, harmlessness, low toxicity, non-flammability, high density and stability. A major weakness of most PCMs is their low thermal conductivity that leads to unsuitable heat transfer to and from the PCM. Hence, several models and techniques have been applied to improve the thermal conductivity and to optimize the performance of LHTES systems, such as including finned tubes of different configurations, bubble agitation, shell and tube (multi-tubes), micro-encapsulating the PCM, insertion of metal matrix into the PCM and the use of heat pipes (HPs). HPs are highly effective passive device for transmitting heat at high rates over considerable distances with extremely small temperature drops, exceptional flexibility, simple construction, and easy control with no external pumping power [3]. The general observations drawn from the various studies demonstrate that, irrespective of the PCM used, the heat transfer characteristics of the LHTES can be improved using any of the listed enhancement techniques, but the effectiveness of each one of them depends on many influential factors [4]. Increasing the heat transfer area on the PCM side is the most simple and efficient method. However, in case that the working fluid passes through the PCM storage tank, extending the piping length inside the tank causes a large increase in the pressure drop of the working fluid and a large decrease in the effective PCM storage volume for conventional LHTES systems. Integrat-

Abbreviations: CSP, concentrating solar power; HP, heat pipe; HTF, heat transfer fluid; LHTES, latent heat thermal energy storage; ODE, ordinary differential equation; PCM, phase change material; PDE, partial differential equation; SD, solar dynamic; SWH, solar water heater; COP, coefficient of performance; HVAC, heating, ventilation, and air conditioning.

* Corresponding authors.
E-mail addresses: sajad.naghavi@um.edu.my (M.S. Naghavi), h.metselaar@um.edu.my (H.S.C. Metselaar).

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ing HPs into the system might overcome this problem. HPs are used to increase the charging/discharging rates and are also used to transfer heat from a source to the storage like solar applications or from the storage to a sink like electronic device cooling applications.

This review critically discusses papers describing hybrid configurations of LHTES and HP systems, where HPs are used as an intermediate device between heat source and LHTES unit. Four main sections are considered. Section 1 succinctly lists the earlier review papers about PCMs and HPs. Section 2 categorizes applications of HP–PCM; to be able to trace the developments and highlight priorities of researches and how these are linked together. Section 3 consists of analytical approaches to be able to compare how different theories address this issue. Section 4 sums up what is known at this time about the effective parameters that play an important role in the performance of the system.

2. Overview of earlier review papers

To be able to have a precise look through the content of this review, it is necessary to survey the outlines of previous review papers published in the fields relevant to LHTES, HP and heat transfer enhancement techniques. Table 1 lists review papers in the field of the LHTES applications, characteristics and analysis methods, whereas Table 2 lists the review papers about HP technologies, configurations, opportunities, and challenges.

3. Applications

This section categorizes configurations of hybrid HP–LHTES systems in different applications. These applications are mostly low temperature solar systems, concentrated solar systems, heat exchangers, cooling systems and those used PCM as an internal TES in HP.

3.1. Low temperature solar collectors

Probably, for the first time at 1978, Abhat [37] took into account the idea of the amplification of the melting–freezing process rate of the PCM by incorporating HPs. He studied, the performance of a finned HP inserted into a PCM container for solar heating applications (Fig. 1). The charging time and temperature gradients between HP and PCM for two different storage substances were investigated. Experimental tests were conducted for a small 1:6 model filled with Paraffin as the PCM. The results of this study indicated that the heat exchanger concept is capable to operate within smaller temperature swings (less than 10 °C) for realistic heat input rates.

A few years later, in another research, Abhat [38] reviewed the essential parameters that need to be undertaken for a low temperature solar thermal system and also studied different configurations of the hybrid HP–TES for low temperature solar heating applications in many aspects. Many parameters like suitable PCM and heat exchanger design for higher thermal conductivity, sensible and latent heat storage and importance of stratification in hot

Table 1
Review papers relevant to PCM material, applications & analysis.

Reference	Subject	Remarks
Zalba et al. [5]	Thermal energy storage by PCM	Material classification, thermophysical properties, stability, heat transfer & applications
Sharma and Sagara [6], Sharma et al. [7]	LHTES applications & systems	Suitable PCMs to enhance the heat storage; measurement techniques of thermophysical properties, studies on thermal cycles for long term stability, corrosion of the PCMs
Sharma et al. [7]	PCMs applications & systems	Detailed study of LHTES systems and applications, heat transfer enhancement techniques
Regin et al. [8]	Characteristics of PCMs for TES system	Evaluation of aspects of PCMs which are material, encapsulation, heat transfer, applications & new material preparation technologies
Agyenim et al. [4]	Integrations methods of PCM to TES systems	PCMs investigated over the last three decades, the heat transfer & enhancement techniques, analysis methods, geometry & configurations of PCM containers were gathered
Kenisarin [9]	High temperature PCMs for TES	High temperature PCMs thermophysical properties, compatibility, long term characteristics & commercialization problems
Jegadheeswaran and Pohekar [10]	Performance enhancement in LHTES systems	Different thermal enhancement techniques like extended surfaces, multiple PCMs, impregnation of porous material, dispersion of high conductivity particles & microencapsulation
Fan and Khodadadi [11]	Thermal conductivity enhancement of PCMs	A variety of PCMs, operating conditions, heat exchanger & thermal energy storage arrangements were covered
Liu et al. [12]	Heat transfer enhancement techniques	High temperature PCMs & heat transfer enhancement techniques (high conductive materials, fins, intermediate heat transfer medium, multiple PCMs & HPs) for concentrated solar thermal power plants
Sharma et al. [13]	PCMs for low temperature solar thermal systems	Information about potential LHTES systems for low temperature solar thermal systems
Sharma et al. [14]	PCMs in solar cooking	Incorporation of TES to cook at late evening by solar TES units
Shukla et al. [15]	PCMs for solar water heater systems	A summary about the investigations & analysis of TES incorporating with/without PCMs for different types of solar water collectors
Nkwetta and Haghighat [16]	PCM in solar applications	Different configurations of PCMs in hot water tank & solar collector with influencing factors & limitations of each technique
Tian and Zhao [17]	PCMs in solar thermal applications	Various types of low/high temperature solar collectors & TES systems in terms of optimization, heat loss reduction, heat recuperation enhancement & different sun tracking mechanisms
Osterman et al. [18]	PCMs for cooling systems	Using PCMs to improve energy performance of buildings
Al-Abidi et al. [19]	Thermal energy storage for air conditioning systems	Integration of PCMs with heat transfer enhancement techniques, in different parts of the air conditioning networks, air distribution network, chilled water network, heat rejection of the absorption cooling
Oró et al. [20]	PCMs for cold thermal energy	Potential PCM at low temperatures for cooling purposes & parameters like long term stability, encapsulation, heat transfer enhancement
Khudhair and Farid [21]	PCMs in buildings applications	The problems associated with the application of PCMs with regard to the selection of materials & the methods used to contain them
Baetens et al. [22]	PCMs in buildings applications	Different types of PCMs & configurations & weaknesses to be applied in building energy management
Cabeza et al. [23]	PCMs in buildings applications	Information about the requirements of the use of the TES in buildings like technology, classification, availability & problems of materials
Soares et al. [24]	PCMs in buildings applications	A review of several passive LHTES systems with PCMs, their impact on building energy performance & building energy simulation methods
Liu et al. [25]	Simulation methods of PCMs	Heat transfer mechanisms & 1D, 2D & 3D mathematical solutions during charging/discharging processes of PCMs