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A review of phase change material and performance enhancement method for latent heat storage system

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ABSTRACT

Latent heat storage (LHS) is considered as the most promising technique for thermal energy storage, due to its high energy storage density and nearly constant working temperature. However, the lower thermal conductivity of the phase change material (PCM) used in LHS system seriously weakens thermal energy charging and discharging rates. In order to improve the thermal performance of LHS system, a lot of research on performance enhancement have been carried out. This review paper will concern on the development of PCMs and performance enhancement methods for LHS system in the last decade. The available enhancement methods can be classified into three categories: using high thermal conductivity additives and porous media to enhance PCM thermal conductivity, using finned tubes and encapsulated PCMs to extend heat transfer surface, using multi-stage or cascaded LHS technique and thermodynamic optimization to improving the heat transfer uniformity. The comparative reviews on PCMs, corresponding performance enhancement methods and their characteristics are presented in present paper. That will help in selecting reliable PCMs and matching suitable performance enhancement method to achieve the best thermal performance for PCM based LHS system. In addition, the research gaps in performance enhancement techniques for LHS systems are also discussed and some recommendations for future research are proposed.

1. Introduction

New energy development and industrial waste heat recovery are becoming more and more important to solve the increasingly serious problems of energy crisis and environmental pollution. However, both new energies such as solar energy and wind energy, and waste heat in conventional industries are typically unsteady with periodic and intermittent. Thus, thermal energy storage (TES) has been a key technology to ensure new energy and industrial waste heat recovery systems operation with high efficiency and high stability. Studies on high efficient TES technologies have been a scientific concern over the past few decades.

There are three kinds of TES technologies, including sensible heat storage (SHS), latent heat storage (LHS) and thermochemical heat storage (TCHS). LHS system uses phase change material (PCM) as thermal energy storage medium, where thermal energy is stored or retrieved during the phase transition process of PCM, melted from solid to liquid or solidified from liquid to solid. Comparing to SHS system, LHS has larger energy storage density and smaller temperature variation. In addition, LHS has excellent repeatability and controllability compared to TCHS system. So, LHS is considered as the most promising technique for TES in the present stage.

LHS has been successfully applied in solar thermal utilization, industrial waste heat recovery, building energy saving, electronics cooling, etc. With the applications of LHS, many investigations on the performances of PCMs and LHS systems have also been performed. Sharma et al. [1] summarizes the investigation and analysis of the available thermal energy storage systems incorporating PCMs for different applications. Kenisarin [2] reviews the investigations and developments of high-temperature PCMs perspective for storage thermal in the range of temperatures from 120 to 1000 °C. Cardenas and Leon [3] summarizes the comprehensive thermophysical properties of inorganic salt compositions and metallic alloys, which could potentially be used as storage media in a high temperature (above 300 °C) LHS system.

During the applications and investigations, the PCM's low thermal conductivity as the most significant drawback of LHS is becoming more and more obvious, which seriously slows down thermal energy charging and discharging rates. In order to improve the thermal performance of LHS system, a lot of research on PCMs and the performance

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enhancement techniques have been carried out over the past decades. Those research results provide valuable reference for the performance enhancement and optimization of LHS system. Jegadheeswaran and Pohekar [4] summarizes the performance enhancement techniques reported in the literature before 2009, where the influence of enhancement techniques on the thermal response of PCM in terms of phase change rate and amount of latent heat stored/retrieved has been addressed. Fan and Khodadadi [5] reviewed the experimental/computational studies to enhance the thermal conductivity of PCM that were conducted before 2010. Liu et al. [6] also reviews the experimental and theoretical methods to enhance PCM thermal conductivity and the thermal conductivity inserts/ additives in recent investigations are listed and summarized.

This review paper will concern on the development of phase change material and performance enhancement methods for LHS system in the last decade (from 2007 to present). The previous works can be found in Ref. [1–6]. The comparative reviews on different kinds of PCMs, the corresponding enhancement methods and their characteristics will be presented in present paper. That will help in selecting reliable PCM and performance enhancement method to achieve the best thermal performance for PCM based LHS system. In addition, the research gaps in the present performance enhancement methods for LHT systems will be discussed and some recommendations for the future research will be proposed.

2. Classification of performance enhancement methods for LHS system

The basic heat transfer equation for an arbitrary heat transfer process can be expressed as

$$\Phi = KA\Delta t \tag{1}$$

where, Φ is heat transfer rate, W; K is heat transfer coefficient between cold and heat objects, W m^{-2} K^{-1}; A is heat transfer area, m^2; Δt is heat transfer temperature difference. According the equation, it can be found that there are three key parameters (K, A and Δt) which are positive correlation with heat transfer rate. So, although an extensive research is carried out in performance enhancement of LHS system, totally speaking, the performance enhancement methods can be classified into three categories as shown in Fig. 1: enhancing PCM thermal conductivity, extending heat transfer surface and improving uniformity of heat transfer process.

2.1. Enhancing PCM thermal conductivity

According to Eq. (1), increasing heat transfer coefficient (K) is an efficient way to enhance LHS rate. K is the reciprocal of total thermal resistance, including HTF side thermal resistance, PCM side thermal resistance and wall thermal resistance. In order to increase the heat transfer coefficient, the total thermal resistance must be decreased. For most of the LHS process, the total thermal resistance is dominated by PCM side thermal resistance. Therefore, the first performance enhancement method for LHS system is to decrease PCM side thermal resistance by enhancing PCM thermal conductivity. The high thermal conductivity porous media and nanoparticles are commonly used to form stable composite PCM (CPCM), which can efficiently enhance PCM thermal conductivity [7–9].

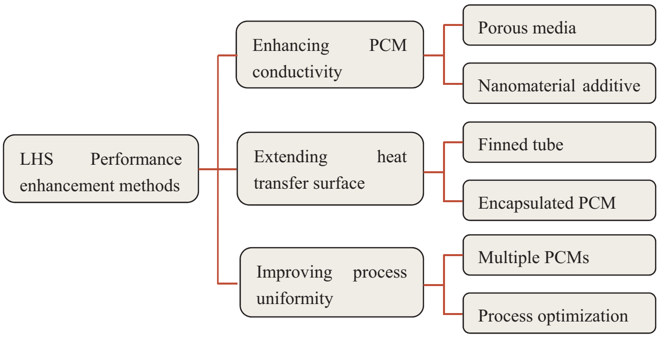

Fig. 1. Classification of performance enhancement methods for LHS system.

2.1.1. Porous media

When porous media is used, PCM is filled into the porous media to form CPCM. The porous media must have high thermal conductivity to efficiently enhance PCM thermal conductivity, high porosity to ensure enough PCM filled and keep high energy storage density. Metal foams such as copper [10–14], nickel [11,15] and aluminum foams [16], expanded graphite foams [17–29] and some expanded rocks such as perlite [30] and vermiculite [31] are used as the porous supporting material. The schematic diagrams for metal foams and metal foams CPCM are shown in Fig. 2.

2.1.2. Nanomaterial additives

When nanomaterial additives are used to enhance PCM thermal conductivity, the nanomaterial will be dispersed into PCM to form uniform CPCM. The additives must have high thermal conductivity and chemical stability to ensure the PCM thermal conductivity can be efficient enhanced and no chemical reaction occurs. The carbon nanomaterials such as multi-walled carbon nanotubes (MWCNT) [32–40], single-walled carbon nanotubes (SWCNT) [32], graphite [34,36,38,41–43], graphene [36,38,39,44,45] and metal oxide nanoparticles [46–48] or metal nanoparticles [49] are commonly used as additives to enhance PCM thermal conductivity. The microstructures for the carbon nanomaterials/eutectic carbonate CPCMs are shown in Fig. 3.

2.2. Extending heat transfer surface

According to, Eq. (1), the second way to improve heat transfer performance is increasing heat transfer area. Extended heat transfer surface, including finned tubes and encapsulated PCMs are widely used to increase heat transfer area between HTF and PCM and enhance LHS performance.

2.2.1. Finned tube

For shell-and-tube LHS system, the finned tubes are used to enhance the heat transfer performance for both the PCM side and heat transfer fluid (HTF) side. The axially fins [49–54], radially fins [55–60] are commonly used to enhance PCM side heat transfer performance. Some other finned tubes such as dimpled tube, cone-finned tube and helically finned tube [61] are used for the HTF side enhancement. At the same time, some heat pipes and finned heat pipes are also used to enhance PCM thermal performance [62–69]. The fin material must have high thermal conductivity to achieve the better enhancement effect. Fig. 4 shows the structure of the axially finned tube and radially finned tube used for LHS. Recently, Dhaidan and Khodadadi [70] reviewed the analytical, computational and experimental studies on the LHS performance enhancement with high thermal conductivity fins, where some interesting conclusions were derived.

2.2.2. Encapsulated PCM

Another method to extend the heat transfer surface of LHS is using encapsulated PCM, where the PCM are encapsulated to form stable capsules. The capsules are accumulated in LHS container and HTF flows through the gaps among different capsules, as shown in Fig. 5. The heat transfer area can be efficiently augmented by this method. According to the dimensions of the capsules, it can be divided into microcapsules [71–76] and macrocapsules [77–89]. For the microcapsules, the dimensions of the microcapsules are usually in micron level, and the dimensions for the macrocapsules are in millimeter level.