Applied Thermal Engineering 81 (2015) 242–252

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Performance of suspended finned heat pipes in high-temperature latent heat thermal energy storage

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HIGHLIGHTS

- Benefits of using suspended finned HPs in latent heat storage unit are investigated.
- The proposed technique improved the reliability and functionality of LHTES systems.
- The energy extracted increased by 140% compared with baseline case.
- System sizing of LHTES unit for future CSP development was reported.

ARTICLE INFO

Article history:
Received 7 December 2014
Accepted 13 February 2015
Available online 23 February 2015

Keywords:
Heat pipe
Phase change
Fins
Effective properties
Conduction
Solidification
Concentrating solar power

ABSTRACT

This study presents a thermal network model for evaluating heat transfer enhancement in a high-temperature latent heat storage unit incorporating finned heat pipes. The objective of this heat enhanced latent heat storage system was to improve the thermal performance of concentrating solar power plants. In this proposed design, finned heat pipes are used in the heat storage unit as effective heat spreaders. The finned heat pipes are kept in suspension and are adjacent to the heat transfer channel in order to increase the overall heat conductance of the phase change material (PCM). The feasibility of the proposed design was established by conducting experimental measurements of the solidification process. The results have shown that the performance was significantly improved by adding finned heat pipes, especially at the later stage of PCM solidification. The performance enhancement was quantified based on heat pipe effectiveness. It was found that the effectiveness of the twelve-heat pipe configuration reached 2.4 after 5 h of simulated operation. In addition, a preliminary system sizing was conducted in order to estimate the system size required for 50 MW electrical power output.

1. Introduction

With fuel price growth over recent decades, global exploration for alternative energy sources has attracted numerous researchers. Specifically, of renewable energy sources, solar energy is attractive because it is clean, abundant and a non-emission energy source which has the possibility to be a major future power generator in sustaining human activities. Concentrating solar power (CSP) is increasingly considered because it facilitates harvesting large amount of solar thermal energy. However, problems associated with solar energy are the intermittency of solar radiation and the relatively high operating cost for solar-electricity generation [1,2]. In order for CSP plants to be operationally cost competitive and efficient, they must be able to harvest and store the maximum solar thermal energy during the period of solar availability, and to utilize the stored heat for continuous electrical power generation. Hence, effective and high density thermal energy storage is an essential component in CSP system development.

There are three types of thermal energy storage that can be utilized in CSP plants. They are sensible heat thermal energy storage (SHTES), latent heat thermal energy storage (LHTES) and thermochemical energy storage (TCES). Currently, only SHTES technique can be used in large scale CSP plants [3]. The SHTES can be subcategorised into liquid SHTES and solid SHTES. The two-tank

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http://dx.doi.org/10.1016/j.applthermaleng.2015.02.030
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molten salt system, in which molten salt is used as storage material, is a liquid SHTES system. It consists of two insulated storage tanks where the first is used to store molten salt at approximately 290 °C (cold tank) and the other for storing molten salt at approximately 390 °C (hot tank). In contrast, the solid SHTES system consists of a tubular heat exchanger embedded in a high-performance concrete [4,5]. One of the major drawbacks of the SHTES systems is the requirement for large quantities of storage material [6]. For example, the storage material required to drive a 50-MW turbine for 9 h is approximately 42,288 tons of salt for the liquid SHTES [7], while it is 50,000 m^3 of concrete for the solid SHTES [8].

In the authors' opinion, using higher density thermal energy storage can directly reduce the development costs of CSP plants, in terms of smaller installation space and reduced heat storage material requirements for thermal energy storage system. In this latter consideration, LHTES has the advantages over SHTES through using phase change material (PCM) for storing solar thermal energy. In addition, LHTES is capable of minimizing the temperature rise during heat charging and discharging. However, the low thermal conductivities of PCMs (typically ~0.5 W/m·K) have limited their thermal potentials. Several thermal enhancement techniques for improving the heat transfer performance of LHTES systems can be found in the published literature. Examples of such techniques are: use of extended surfaces (fins), employing multiple PCM's, metal matrix, metallic fillers and micro-encapsulation [9,10].

In this paper, heat pipes (HPs) are implemented in an LHTES system for high temperature applications and are similarly applicable to CSP systems. Generally, HPs are passive heat transfer devices which can transfer large amounts of heat rapidly from one point to another using a small temperature drop. They are often considered as “superconductors” of heat as they possess effective thermal conductivity several hundred times than that of copper [11]. Using HPs in LHTES is not a new technique for improving heat transfer performance and many researchers have presented proposals for improving the aforementioned heat transfer limitations. For examples, Shabgard et al. [12] developed a numerical model to predict the transient response of a high-temperature LHTES system used for solar thermal electricity generation. They investigated two storage configurations; one with PCM around a tube conveying the heat transfer fluid (HTF), and the second with the PCM enclosed within a tube over which the HTF flows. The numerical results showed that adding HPs improved thermal performance of the LHTES system. Nithyanandam and Pitchumani [13] used a similar numerical model combined with a numerical optimization scheme to maximize the transferred energy and the effectiveness. They concluded that the effectiveness of the HPs decreases if the HTF mass flow rate, module length, and tube radius are increased. Robak et al. [3] evaluated the integration of LHTES into large scale CSP applications in terms of economic aspects. The LHTES design evaluated was embedded gravity-assisted wickless HPs (thermosyphons). Their objectives were to reduce the size and amount of materials needed for heat storage in CSP applications. The results showed that the proposed design has the potential to reduce the capital cost by at least 15% compared to the current two-tank SHTES technology. Later, the design proposed by Shabgard et al. [12] has been evolved by Khalifa et al. [14]. They used axially finned HPs rather than bare HPs in the LHTES unit. Their results showed that, the energy extracted increased by 86% and the heat pipes effectiveness increased by 24%. Furthermore, it was reported in the same study that the required number of HPs was reduced by 30% for a 9 h storage unit incorporated in a 10MW$_e$ CSP plant.

In relation to the studies mentioned above, issues of structural integrity between the HTF and HPs regions under high temperature and corrosive environments (due to molten salt) have not been addressed. Consequently, the objective of the present study is to propose a new heat enhancement configuration using HPs for LHTES which can reduce potential structural failures such as leakage after prolong usage. This heat enhancement proposal is a simple design which can improve the durability of the heat transfer structures and improve the CSP plant's operational reliability. A thermal network model was developed to investigate numerically the performance of suspended finned HPs in a High-temperature LHTES unit.

2. System design description

In this new heat enhancement design of an LHTES unit, the HTF channels are not penetrated by any HP which differs from the design presented by Shabgard et al. [12]. Studding HPs into HTF channels is complex in fabrication and possesses risks of structural failure (leakage) because of repetitive heating and cooling under harsh condition. To avoid such undesired risks, the proposed heat enhancement technique is to position HPs in suspension arrangements adjacent to the outer surfaces of the HTF channels (see Fig. 1a). A unit model cell of length L_m has been defined for the purpose of numerical analysis, and is shown in Fig. 1b. To enhance the heat transfer rate, the HPs are equipped with high thermal conductance fins for better heat spreading between the HPs and the PCM. The fins are kept vertical in order not to dampen the natural convection currents occurring during the charging process, whereas the HPs are kept horizontal in order to transfer the same heat during the charging and discharging processes. Fig. 1 shows the proposed design.

As has been shown numerically by Shabgard et al. [12] and experimentally by Robak et al. [15], the discharging stage is the limiting stage as it is much slower than the charging stage. Therefore, only the solidification mode is considered in this study.

3. Mathematical modelling

In the proposed design, there are two regions of solidification; one around the HPs and the second around the HTF channel wall (see Fig. 2, top left and top right). A thermal network model has been developed to simultaneously simulate the solidification associated with these two regions. The numerical model developed firstly computes the solidification around the HTF channel based on the temperature distribution and the solidification front position. Then the solidification around the HPs is considered assuming that the condenser length of each HP is equal to the thickness of the solidified PCM around the HTF channel (s_t). For each time step, this procedure is repeated until the amount of energy transferred from the liquid PCM, through the HPs, matches that released into the solid PCM adjacent to the HTF channel (this is discussed in section 3.2).

$$\frac{dT_i}{dt} = \frac{2\alpha_i}{\lambda_i^2}\left(T_{i,1} + T_{i,2} - 2T_i\right) + q'''V_i \tag{1}$$

To simplify modelling, the following assumptions are made.

a. The thermal resistances of the HP associated with the vaporisation and condensation processes [11] are ignored.
b. Only pure conduction heat transfer is considered. This assumption is justified since the initial temperature is the freezing point, T_m, of the PCM [16].
c. The PCM is assumed isotropic and homogeneous.