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Performance enhancement of high temperature latent heat thermal storage systems using heat pipes with and without fins for concentrating solar thermal power plants

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A key drawback of using latent heat thermal storage systems for concentrating solar thermal power plants is the low thermal conductivity of the phase change material during the melting and solidification processes. This paper investigates an approach for reducing the thermal resistance by utilising axially finned heat pipes. A numerical model simulating the phase change material melting and solidification processes has been developed. This paper also includes the models of the evaporation and condensation of the heat pipe working fluid. The results show that by adding four axial fins and including the evaporation and condensation, the overall thermal performance of the storage system is enhanced significantly compared to having bare heat pipes. After 3 h a total of 106% increase in energy storage is obtained during the charging process. The results also show that the combined effect of incorporating the evaporation/condensation process and adding the fins leads to a threefold increase in the heat storage during the first 3 h. During the discharge process, there was a 79% increase in energy discharged and also the combined effect of incorporating the evaporation/condensation as well as adding the fins results in an almost four fold increase in the heat extracted within the first 3 h. A parametric analysis has also been carried out to analyse the effect of the finned heat pipe parameters after incorporating evaporation and condensation of the heat pipe working fluid.

1. Introduction

In a concentrating solar power (CSP) plant, a latent thermal energy storage system (LTESS) is ideal because of its constant storage temperature and high energy storage density [1–4]. Compared to sensible energy storage, a LTESS needs less storage volume. Potentially, this can result in a less expensive thermal storage system for CSP plants.

Through the charging and discharging processes, the operation of a LTESS involves the exchange of energy between the heat transfer fluid (HTF) and the phase change material (PCM). During the charging process, the solar receiver heats up the HTF which then flows through the LTESS to melt the solid PCM at a constant temperature. The cold HTF during the discharging process flows through the LTESS, which contains the PCM in a molten state, and heats up the HTF. This can then be used to generate electricity in a CSP plant. The melting process takes place when the sun's energy is available; the solidification process occurs when the supply of solar energy is unavailable, insufficient or when there is an electricity peak demand. The charging process of the PCM is convection-dominated and the discharging process is conduction-dominated; this has been demonstrated by many researchers in the field of LTESSs [5–8]. Lacroix [9] developed a theoretical model to predict the transient behaviour of a shell and tube storage system with PCM. This work showed that the low thermal conductivity of the PCM is a basic drawback of a LTESS, which leads to low rates of heat transfer and a delayed response of the PCM system.

Several techniques are reported in the literature for reducing the thermal resistance within the PCM. Sari et al. [10] proposed microcapsules containing n-octacosane as PCM for thermal energy storage. Jegadheeswaran and Pohekar [11] reviewed literature on enhancing the performance of a LTESS. For additional heat transfer area, fins can be used [12,13]. In order to maintain constant heat

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flux to the phase change materials along the HTF flow direction the melting temperatures have been investigated. Exfoliated graphite nanoplatelets are used by other techniques. [14,15], which distribute nanoparticles in the PCM to increase its thermal conductivity [16–18].

Bauer [19] developed an analytical model to investigate the effective utilisation of fins in LTESSs. The solidification times of PCMs using two geometries were evaluated; namely a plane wall and a tube surrounded by PCM. Mosaffa et al. [20] presented a two-dimensional analytical model to study the solidification process of a PCM in a shell and tube heat exchanger with radial fins. They reported that the PCM solidified more quickly in the cylindrical shell than in the rectangular storage. In addition, the solid fraction of the PCM increased more quickly when the cell aspect ratio is small. Ismail et al. [21] investigated numerically and experimentally the effect of fin design parameters, such as fin length, fin thickness, number of fins, and the aspect ratio of the annular space on the complete solidification, solidified mass fraction and the total stored energy of the PCM. Len et al. [22] investigated experimentally the melting and solidification characteristics of $CaCl_2.6H_2O$ as a PCM in a vertical two-concentric pipe energy storage system. Different design and operating parameters were studied, such as the number of fins inside the PCM, mass flow rate, and the inlet HTF temperature. They reported that the effect of the design parameters was more significant than the effect of the operating parameters. Esen et al. [23,24] investigated theoretically the performance of a solar assisted cylindrical energy storage tank. The results show that to optimize the performance of the tank the PCM cylinder radius, the mass flow rate, and the inlet temperature of the HTF must be chosen carefully and also developed a theoretical model to analyse the influence of various thermal and geometric parameters on the PCM melting time for different PCMs and tank configurations. Their results show that the duration time of the PCM melting depends on not only thermal and geometric parameters, but also on the thermophysical properties of the PCM. Lipnicki and Weigand [25] studied experimentally and theoretically the natural convection and solidification of a vertical annular enclosure. The inner cylinder was cooled down below the solidification temperature of the HTF (water), whereas the outer was kept at a constant temperature above zero. They reported that the influence of the contact layer between the frozen layer and the cold surface was of significant importance to the solidification process. Tay et al. [26] compared different pin and fin configurations for the tube-coiled PCM thermal energy storage for heat transfer enhancement. The results indicated that the finned tube performed better than using pins as demonstrated through higher average effectiveness as well as shorter phase-change duration. They concluded that the use of fins is a more effective heat transfer-enhancement technique for all shell-and-tube-type PCM thermal storage systems. Tay et al. [27] also investigated dynamic melting, and found that it can nearly double the effective thermal conductivity of the PCM. Esen et al. [28] developed a theoretical model and validated experimentally to analyse the thermal performance of the solar-aided latent heat storage tank in the charging and discharging process. The results showed reasonable agreement between theoretical and experiment.

Enhancing the energy transfer between the PCM and the HTF using heat pipes has also been investigated. Liu et al. state that heat pipes have high thermal conductivity and they can be combined with phase change thermal storage systems to use as thermal channels between the HTF and the PCM [29]. Esen et al. [30,31] fabricated and analysed experimentally a solar systems using vacuum-tube collectors with heat pipes and the thermal performance of a thermosyphon heat pipe solar collector under real operating conditions using three different refrigerants. The study concluded that the thermophysical properties of the refrigerant used in the heat pipes are important, and also using a thermosyphon, the experimental results were compared to those in the literature and found to be in good agreement. Using heat pipes in low temperature applications has been analysed numerically and experimentally by Tardy and Sami [32]. They used air as the HTF to analyse the heat transfer in the system. Shabgard et al. [33] used heat pipes in PCM using a thermal network model. To optimise the design [34], used the same model developed in Ref. [33]. They concluded that increasing the mass flow rate of the HTF, length of the system and radius of the tube led to a decrease in the heat pipes effectiveness. In contrast, increasing the condenser section length, the evaporator section length and the radius of the vapour core led to an increased effectiveness of the heat pipes.

This paper builds on the system presented in Ref. [33], which utilises bare heat pipes in a LTESS. While fins on tubes in PCM systems have been studied and are reported in the literature, the benefits of adding fins to heat pipes in PCM systems has only been described by Khalifa et al. [35]. They conducted a numerical and experimental investigation on the thermal performance of a LTESS which used finned heat pipes for heat transfer enhancement. Their results showed that there was an 86% increase in energy extracted from the PCM and the heat pipe's effectiveness improved by 24%, when compared to the case of heat pipes with no fins. Khalifa et al. [35] investigated the solidification of the PCM only, and also they did not include in the model the effect of evaporation and condensation of the heat pipe working fluid. The work in this paper investigates the impact of adding axial fins to the heat pipe and also analyses the impact of incorporating the evaporation and condensation of the heat pipe working fluid on the charging and discharging rate. All researchers to date have modelled the heat pipe in LTESS as a highly conductive solid material. This paper is the first that incorporates the evaporation and condensation of the heat pipe working fluid using multiphase flow heat transfer relations. Furthermore, a comprehensive parametric analysis is carried out to analyse the influence of specific parameters on the thermal performance of the LTESS.

2. Problem description

The LTESS considered here, uses a HTF to exchange thermal energy with a PCM. The geometry of a heat pipe which has been used as the heat transfer enhancement technique between the HTF and PCM is presented in Fig. 1a. Four heat pipes are spread in each HTF tube over the system length L_m, which is the length of the system used in this study (see Fig. 1b). The finned heat pipe (Fig. 1c) has been used in the calculation to analyse the difference between a bare and finned heat pipe in terms of heat transfer. The fins shown in Fig. 1c have 0.14 m length, 0.01784 m height and 0.001 m thickness. The HTF passes through tubes that are embedded within the shell-side PCM (Fig. 2). PCM phase change rates evolve in response to various heat transfer processes. In addition, the evaporation/condensation part as the main mechanism on the heat pipe has been included in the analysis. Conduction and free convection heat transfer relations are applied to calculate the total amount of energy stored and extracted from the PCM. The objective of this study is to investigate the potential benefits associated with incorporating bare and finned heat pipes in the LTESS including analysing the effect of the evaporation/condensation part of the heat pipe.

3. Mathematical modelling

Shabgard's design of a LTESS with embedded heat pipes [33] was adopted in this study. The model is based upon the following