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Simulation of heat pipe-assisted latent heat thermal energy storage with simultaneous charging and discharging

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ABSTRACT

Melting and solidification of a phase change material (PCM) held within a vertical cylindrical enclosure that is integrated with a heat pipe (HP) is simulated as a single module. The HP is heated from the bottom to melt (charge) the PCM that is positioned in the middle of the HP length, and is cooled from the top to solidify (discharge) the PCM. Three modes of operation are considered in this study (i) charging-only, (ii) simultaneous charging and discharging, and (iii) discharging-only. All modes of operation are handled with a single HP within a PCM (single HP-PCM) of which the top and bottom sections are inactivated during charging-only and discharging-only modes, respectively. A parametric study of the influence of the PCM enclosure height and input/output heat transfer rates shows that, for the same mass of PCM, a longer enclosure exhibits a lower HP bottom average wall temperature and relatively more PCM melting during simultaneous charging and discharging. Increasing either the input, output, or both heat transfer rates has a significant effect on the temperature of the HP bottom and top sections, but only a minor impact on the temperature of the HP middle section.

1. Introduction

Concentrating solar power (CSP) plants harvest solar energy in the form of heat that can be stored in thermal energy storage devices and is ultimately used to produce electricity. The need for energy storage is due to the intermittent availability of solar irradiation and to provide a balance between the supplied loads and the demand (load leveling) during the evening hours when peak utility loads may be present.

Energy can be stored either as sensible heat or latent heat; latent storage is preferred due to its high volumetric energy density and potentially lower cost [1–5]. The temperature of the phase change material (PCM) remains nearly constant during melting (charging) and solidification (discharging) which is desirable. However, the low thermal conductivity of most PCMs limits their use in solar thermal energy generation. To alleviate this challenge, different approaches have been proposed such as dispersing high thermal conductivity particles within the PCM [6,7], using high thermal conductivity porous matrices embedded within the PCM [8,9], micro-encapsulating the PCM [10,11], and incorporating of extended surfaces and/or heat pipes (HPs) [12–19]. HPs are passive devices which utilize liquid–gas phase change to efficiently transfer heat over a long distance with a small cross-sectional area [19]. HPs can be manufactured into a variety of configurations and operational temperature ranges depending on the specific system. When HPs are embedded in the PCM, they can increase the effective thermal conductivity of the PCM significantly. Faghri holds two patents [20,21] for the incorporation of HPs into PCMs for latent heat thermal energy storage (LHTES) systems. The high volumetric energy density and nearly isothermal behavior of the latent storage is particularly advantageous to dish–Stirling systems due to the isothermal heat input requirement of Stirling engines [22].

Recent investigations have considered various aspects of integrated HP-PCM systems. Liu et al. [23] experimentally investigated a HP-heat exchanger consisting of a circumferentially-finned copper-acetone thermosyphon with stearic acid ($T_m = 52.1$ °C) as the PCM. Heating (charging) and cooling (discharging) was induced by water flowing in two separate channels at the bottom and top of the PCM. The effects of the water inlet temperature and mass flow rate were studied. In continuation, Liu et al. [24] used the same experimental setup to investigate simultaneous charging and discharging. Heat was transferred from the hot water stream

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Nomenclature

c	specific heat (J/kg K)
c_p	specific heat at constant pressure (J/kg K)
c_v	specific heat at constant volume (J/kg K)
D	diameter (m)
f_ℓ	volumetric PCM liquid fraction
g	gravitational acceleration (m/s^2)
h	enthalpy (J/kg)
h_{fg}	latent heat of evaporation (kJ/kg)
$h_{s\ell}$	latent heat of fusion (kJ/kg)
k	thermal conductivity (W/m K)
L_a	HP adiabatic section length (m)
L_B	HP bottom section length (m)
L_M	HP middle section length (m)
L_T	HP top section length (m)
p	pressure (Pa)
q	heat transfer rate (W)
r,z	coordinate directions (m)
R	gas constant (J/kg K)
s	source term in the temperature transforming model
t	time (s or h)
T	temperature (K)
T_m	melting temperature (K)
u	velocity component (m/s)

Greek

β	thermal expansion coefficient (K^{-1})
δT	half width of temperature range (K)
Φ	viscous dissipation (J/kg m^2)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

B	bottom
e	enclosure
eff	effective
hp	heat pipe
i	wick-vapor interface, inner
ℓ	liquid phase of PCM
o	outer
r,z	coordinate directions
ref	reference
s	solid phase of PCM
sat	saturation
T	top
υ	vapor phase of heat pipe working fluid
w	wall of the heat pipe

in the bottom channel through the HPs to the cold water stream in the top channel. Depending on the operational conditions, the PCM either absorbed or released thermal energy. A criterion based on a thermal resistance analysis was developed to predict whether the PCM absorbs or releases heat.

Robak et al. [25] experimentally investigated separate charging and discharging of n-octadecane housed in a cylindrical enclosure with five embedded HPs. The system was heated and cooled from below with a heat transfer fluid (HTF). The relative performance of the HPs was compared to a fin-assisted case and a non-HP, non-fin case. The results showed that the HP-assisted configuration increased melting and solidification rates compared to the non-fin, and fin-assisted cases.

A thermal network model was developed by Shabgard et al. [26] to simulate separate charging (melting) and discharging (solidification) of a LHTES system for CSP applications. Multiple HPs were installed between the HTF and PCM in two configurations; one with the PCM contained within a tube over which the HTF flowed, and a second with the PCM surrounding a tube that carries HTF. A heat pipe effectiveness, defined as the ratio of heat transfer in the system with HPs to that of a system without HPs, was used to quantify the improvement in heat transfer due to the HPs. In a related work, Shabgard et al. [27] performed a heat transfer and exergy analysis of a large scale, cascaded LHTES system using thermosyphons for CSP. The transient response of the LHTES during either charging and discharging was predicted. The optimum arrangement of HPs in two HP-assisted LHTES configurations was identified by Nithyanandam and Pitchumani [28]. The configurations were (*i*) a PCM housed inside tubes exposed to a cross flow of HTF, and (*ii*) a PCM surrounding the HTF tubes.

The two-dimensional transient response of a conjugate HP-PCM system including the effects of natural convection was numerically simulated by Sharifi et al. [29]. A vertically-oriented HP was concentrically embedded in a PCM held in a cylindrical enclosure. The melting process of the HP-PCM arrangement was compared with melting induced by an isothermal surface, a solid rod, and a hollow tube, all of the same height and outer diameter as the HP. It was shown that the HP significantly enhanced the melting rate compared to that of rods or tubes. It was found that the effectiveness, defined as the volumetric liquid fraction of the HP-PCM relative to the volumetric liquid fraction of the Rod-PCM, of the HP-PCM was doubled compared to the Rod-PCM. It was also shown that the HP-PCM is particularly effective, compared to the Rod-PCM, in increasing the melting rate in a system heated from above.

Recently, it has been suggested that the application of LHTES to dish-Stirling CSP systems may be desirable due to the match between the near isothermal input requirements of Stirling engines and the near isothermal nature of phase change processes [22]. Specifically, Sandia National Laboratories has proposed a LHTES design for dish-Stirling systems that involves multiple dual HP-PCM modules. A dual HP-PCM module is comprised of two HPs, one of which is associated with charging the PCM (encompassing only the hot source and PCM) and the other with discharging the PCM (only the PCM and cold source). The full-scale system, as proposed in [22], consists of multiple dual HP-PCM modules which contain two distinct sets of HPs, where one set is for charging the PCM and the other for discharging the PCM. This configuration leads to a complicated three-dimensional behavior involving distinct as well as simultaneous charging and discharging. A simplified two-dimensional configuration was analyzed by Shabgard et al. [30] to approximate the three-dimensional configuration of [22], based on a physically-reasonable geometric argument. The investigators studied three modes of operation for a typical daily cycle: (*i*) charging-only, (*ii*) simultaneous charging and discharging, and (*iii*) discharging-only. Systems with various geometrical configurations were investigated.

Few HP-PCM studies account for simultaneous charging and discharging, a situation relevant to the Sandia dish-Stirling engine concept. Therefore the objective of this study is to simulate the melting and solidification processes of a PCM induced by a HTF to a single HP for three different modes of operations: Mode I (charging-only), Mode II (concurrent charging and discharging)