Renewable Energy 69 (2014) 134–146

Contents lists available at ScienceDirect

Renewable Energy

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

Phase change material with graphite foam for applications in high-temperature latent heat storage systems of concentrated solar power plants

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ARTICLE INFO

Article history:
Received 1 November 2013
Accepted 12 March 2014
Available online

Keywords:
Concentrated solar power
Graphite foam–$MgCl_2$ combination
Latent heat thermal energy storage
Three-dimensional heat transfer simulation
Exergy efficiency

ABSTRACT

A high-temperature latent heat thermal energy storage (LHTES) system was analyzed for applications to concentrated solar power (CSP) plants (utilizing steam at ~610 °C) for large-scale electricity generation. Magnesium chloride was selected as the phase change material (PCM) for the latent heat storage because of its high melting point (714 °C). Because the thermal conductivities of most salt materials are very low, usually less than 1 W/m K, graphite foam was applied as an additive to considerably enhance the overall thermal conductivity of the resulting graphite foam–PCM combination in the LHTES system. The heat transfer performance and the exergy efficiency in the graphite foam–$MgCl_2$ LHTES system were considered for the design and optimization of the storage system. Three-dimensional (3-D) heat transfer simulations were conducted for the storage system using commercial software COMSOL. Three groups of analyses were performed for an LHTES system: using PCM alone without graphite foam, using average material properties for graphite foam–PCM combination, and using anisotropic thermal conductivity and temperature-dependent material properties for graphite foam–PCM. Results presented show that the graphite foam can help to significantly improve the heat transfer performance as well as the exergy efficiency in the LHTES system. They also show the effects of the anisotropic thermal conductivity and indicate capital cost savings for a CSP electric power plant by reducing the number of heat transfer fluid (HTF) pipes in the LHTES tank by a factor of eight.

1. Introduction

Thermal energy storage (TES) systems have been proposed for applications to CSP plants to store solar thermal energy in the daytime for usage when the sun is down in order to improve the plant capacity. Two general approaches have been applied to TES: sensible heat storage and latent heat storage. Existing CSP plants in the world use sensible heat storage systems for medium operation temperatures (less than 600 °C). For instance, Gemasolar in Seville, Spain uses the central tower technology and a molten salt, sensible heat storage system for solar power generation [1,2]. A two-tank direct system with liquid-state salts (60 mol% $NaNO_3 + 40$ mol% kNO_3) is used for the sensible heat storage. The plant capacity is 17 MWe with 15-h storage capacity [1,2]. Another example is Extresol-1 in Badajoz, Spain [1,3]. It also uses a two-tank, molten salt, sensible heat storage system. It has applied the parabolic trough technology and an indirect storage system [1,3], which requires an extra heat exchanger and pumps in the storage cycle. The plant capacity is 50 MWe with 7.5-h storage capacity [1,3]. Due to the large size and high cost of sensible heat storage systems, LHTES systems have been proposed for future CSP plants.

Latent heat storage using PCMs is a very promising method to store solar thermal energy. It can store thermal energy at a much higher density based on the latent heat of the material with a smaller volume requirement of the material and a smaller temperature difference. It can reduce the two-tank sensible storage system to a one-tank system decreasing the size and the cost of the storage system and thus simplifying it. Furthermore, latent heat storage can improve the thermal performance of the storage system partially through higher temperature. Fig. 1 is the conceptual energy flow scheme in CSP with LHTES system. In order to achieve

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http://dx.doi.org/10.1016/j.renene.2014.03.031
0960-1481/© 2014 Published by Elsevier Ltd.

Nomenclature

A	cross section area of heat transfer fluid pipe (m^2)
$B(T)$	liquid fraction
c_p	heat capacity (J/kg K)
D	inner diameter of heat transfer fluid pipes (m)
Ex	exergy (J)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	latent heat of fusion (J/kg)
M	mass of the graphite foam–PCM combination in the LHTES system (kg)
n	exponent
Pr	Prandtl number
r	radius (m)
Re_D	Reynolds number in heat transfer fluid pipes
T	temperature (K)
T_a	environment temperature (K)
T_m	melting point (K)
$T_{PCM,char}$	final temperature of graphite foam–PCM after charging process (K)
$T_{PCM,dis}$	final temperature of graphite foam–PCM after discharging process (K)
$T_{PCM,init}$	initial temperature of graphite foam–PCM (K)
t	time (s)
V	heat transfer fluid velocity (m/s)
$d\alpha/dT$	Gaussian function

Greek symbols

μ	dynamic viscosity (N s/m^2)
μ_s	dynamic viscosity at the wall (N s/m^2)
ρ	density (kg/m^3)
ψ	exergy efficiency (%)
$\psi_{overall}$	overall exergy efficiency (%)
ψ_{round}	round trip exergy efficiency (%)

Subscripts

char	charging process
combination_x	graphite foam–PCM combination in the *x*-direction
combination_y	graphite foam–PCM combination in the *y*-direction
combination_z	graphite foam–PCM combination in the *z*-direction
dis	discharging process
HTF	heat transfer fluid
HTF_char	heat transfer fluid during charging process
HTF_char_inlet	inlet heat transfer fluid during charging process
HTF_char_outlet	outlet heat transfer fluid during charging process
HTF_dis	heat transfer fluid during discharging process
HTF_dis_inlet	inlet heat transfer fluid during discharging process
HTF_dis_outlet	outlet heat transfer fluid during discharging process
l	liquid state
s	solid state

Acronyms

CSP	concentrated solar power
DSC	differential scanning calorimetry
FLiNaK	LiF–NaF–KF (46.5–11.5–42 mol%)
HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
PCM	phase change material
TES	thermal energy storage

the large-scale energy usage, the heating requirements of the power cycle in the CSP need to be high to achieve high efficiencies. Moreover, in order to increase the storage capacity for large-scale electricity generation, high melting temperature (above 700 °C) PCMs are being considered for latent heat storage.

In the present study, magnesium chloride ($MgCl_2$) whose melting point is 714 °C [4] was chosen as the PCM for the TES system. Because of the low thermal conductivity of magnesium chloride, aligned ligament graphite foam was introduced to enhance the overall thermal conductivity of the graphite foam–PCM combination. The open porosity of the graphite foam is around 90%, i.e. 90% of volume is occupied by the PCM in the graphite foam–PCM combination. This study concentrated on analyzing the heat transfer performance and the exergy efficiency of the graphite foam–PCM LHTES system. The thermal performance of the storage system was analyzed under various situations through 3-D COMSOL heat transfer simulations.

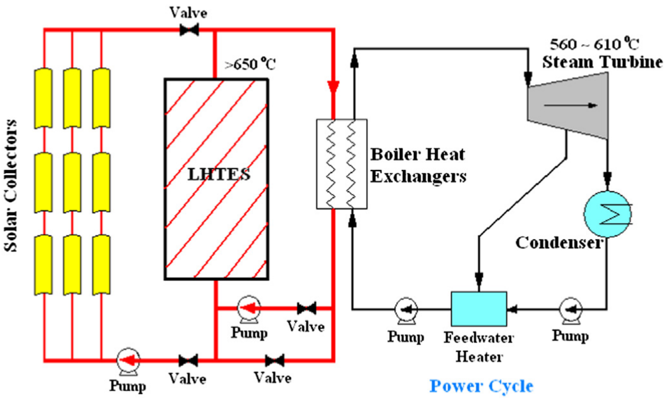

Fig. 1. Schematic of the energy flow in CSP with TES system.

Heat transfer studies are often intended to increase detailed understanding of the heat transfer performance in TES systems in order to help their design and optimization. Currently, there are many investigations into phase change phenomena in this area [5–10]. Nithyanandam and Pitchumani studied the heat transfer performances in a single PCM tube considering the effects of heat pipes and metal foam in the PCM [5]. Yang and Garimella have investigated the melting of a PCM in metal foams including buoyancy-driven convection in the liquid phase PCM in a square enclosure [6]. Lamberg et al. have studied the melting and freezing processes in a PCM both numerically and experimentally [7]. They considered the effects of fins in the PCM storage. For numerical simulations, they introduced two methods, an enthalpy method and an effective heat capacity method, and compared the results of both methods [7]. Li et al. studied melting/solidification problems for phase change using the front-tracking algorithm [8,9]. Voller et al. investigated convection/diffusion phase change problems with the enthalpy method [10]. Nevertheless, most of the investigators focused on a single PCM tube [5] or single PCM domain [6–10]. Few studies are for the storage system. Therefore, the present simulations concentrate on 3-D heat transfer in full scale LHTES tank systems (multiple-pipe systems).