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Optimization of an encapsulated phase change material thermal energy storage system

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Abstract

Thermal energy storage enables uninterrupted operation of a concentrating solar power (CSP) plant during periods of cloudy or intermittent solar availability. This paper presents a transient computational analysis of an encapsulated phase change material (EPCM) thermal energy storage (TES) system for repeated charging and discharging cycles to investigate its dynamic response. The influence of the design and operating parameters on the dynamic charge and discharge performance of the system is analyzed to identify operating windows that satisfy technoeconomic targets of storage cost less than \$15/kW h_t, round-trip exergetic efficiency greater than 95%, charge time less than 6 h and a minimum discharge period of 6 h. Overall, this study illustrates a methodology for design and optimization of encapsulated PCM thermal energy storage system (EPCM-TES) for a CSP plant operation.

Keywords: Thermal energy storage; Encapsulated phase change materials; Concentrating solar power; Design window; Optimization

1. Introduction

Thermal energy storage system is essential to make concentrating solar power (CSP) generation competitive for meeting current and future energy needs. Storing energy for future use allows the power plant to operate continuously during periods of intermittent sun, reduces the mismatch between the energy supply and demand by providing load leveling and helps to conserve energy by improving the reliability and performance of CSP plants. Thermal energy can be stored as either sensible or latent heat (Stekli et al., 2013). Most of the thermal energy storage systems in operation are based on sensible heat storage. Storing heat in the form of latent heat of fusion of phase change material (PCM) in addition to sensible heat significantly increases the energy storage capacity and reduces size of the TES system. However, a major technology barrier that is limiting the use of latent thermal energy of PCM is the higher thermal resistance provided by its intrinsically low thermal conductivity, thus requiring large heat transfer surface area of interaction. Several techniques to improve the thermal performance of latent thermal energy storage systems are reported in the literature; notable among them are embedding heat pipes or thermosyphons between the HTF and PCM (Nithyanandam and Pitchumani, 2011, 2013a, 2014a, 2013b), dispersing high conductivity particles in the PCM (Mettawee and Assassa, 2007) and storing PCM within the framework of porous metal foams (Nithyanandam and Pitchumani, 2014b; Zhao and Wu, 2011). A review of various techniques employed to enhance the performance of high temperature latent thermal energy storage system is discussed in Cárdenas and León (2013). One promising approach is

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Nomenclature

b	capsule wall thickness (m)
b^*	dimensionless capsule wall thickness
c	specific heat (J/kg K)
C^*	cost per unit mass ($/kg)
C'	cost per unit length ($/m)
C''	cost per unit area ($/m^2)
f_L	liquid fraction
h	convective heat transfer coefficient (W/m^2 K)
h_{sl}	latent heat of fusion of PCM (J/kg)
H	height (m)
k	thermal conductivity (W/m K)
k^*	dimensionless thermal conductivity
m	mass flow rate (kg/s)
Nu	Nusselt number
Pe	electrical power output (MW$_e$)
Pr	Prandtl number
P_{th}	thermal power output (MW$_t$)
Q	energy (MJ)
r	radial direction
R	radius (m)
R^*	dimensionless radius
Re	Reynolds number
t	time (s)
t^*	dimensionless time
T	temperature (K)
T_m	melting temperature (K)
U	superficial velocity of heat transfer fluid (m/s)
w	thickness (m)
z	axial direction

Subscripts and Superscripts

1	1 PCM non-cascaded EPCM-TES system
2	2 PCM cascaded EPCM-TES system
3	3 PCM cascaded EPCM-TES system
B	bottom
c	capsule
C	charging
D	discharging
$encap$	encapsulation
f	heat transfer fluid
F	foundation
I	insulation
L	latent
M	middle
p	phase change material
SS	stainless steel
t	tank
T	top
eff	effective

Greek Symbols

α	storage capital cost ($/kW h$_t$)
γ	melt fraction
ε	porosity of the packed bed
ζ	exergetic efficiency (%)
θ	dimensionless temperature
θ_m	dimensionless melt temperature
θ'_C	dimensionless charging cut-off temperature
θ'_D	dimensionless discharging cut-off temperature
λ	capacitance ratio
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
ψ	inverse Stefan number

to increase the heat transfer area between the HTF and PCM by incorporating the PCM mixture in small capsules (Nithyanandam and Pitchumani, 2014c; Mathur et al., 2013; Pendyala, 2012).

Several reports on the numerical modeling of sensible heat storage in packed beds are found in the literature (Schumann, 1929; Shitzer and Levy, 1983; Yang and Garimella, 2010; Beasley and Clark, 1984; Yang and Garimella, 2010; Van Lew et al., 2011; Yang and Garimella, 2013; Wakao and Kagei, 1982). Ismail and Henriquez (1999) presented a mathematical model for predicting the thermal performance of cylindrical storage tank containing spherical capsules filled with water as PCM. The model was used to investigate the influence of the working fluid inlet temperature, flow rate and the material of spherical capsules of fixed (77 mm) diameter on the solidification process. Felix Regin et al. (2008) and Singh et al. (2011) presented a brief review of the works performed in the thermocline storage system till date. Felix Regin et al. (2009) also reported the modeling of thermocline energy storage system with embedded PCM capsules. Wu and Fang (2011) analyzed the discharging characteristics of a solar heat storage system with a packed bed of spherical capsules filled with myristic acid as PCM. The influence of HTF mass flow rate, inlet temperature and the porosity of packed bed were studied.

In developing thermal storage technologies, the exergetic efficiency is sought to be high to ensure that heat quality is maintained after storage (Stekli et al., 2013). Previous investigations focused on latent thermal energy storage systems have shown that cascading several PCMs in the order of their decreasing melt temperatures from the hot HTF inlet side can result in higher heat transfer rates, as well as improved exergetic efficiency due to a more uniform temperature difference between the hot and cold media (Wang et al., 1999; Gong and Mujumdar, 1997). For