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ScienceDirect

Solar Energy 122 (2015) 396–408

SOLAR ENERGY

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Exergetic optimization and performance evaluation of multi-phase thermal energy storage systems

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Received 15 March 2015; received in revised form 17 August 2015; accepted 18 August 2015
Available online 30 September 2015

Communicated by: Associate Editor Luisa F. Cabeza

Abstract

This study outlines a methodology for modeling and optimizing multi-phase thermal energy storage systems for solar thermal power plant (STPP) operation by incorporating energy and exergy analyses to a TES system employing a storage medium that can undergo multi-phase operation during the charging and discharging period. First, a numerical model is developed to investigate the transient thermodynamic and heat transfer characteristics of the storage system by coupling conservation of energy with an equation of state to model the spatial and temporal variations in fluid properties during the entire working cycle of the TES tank. Second, parametric studies are conducted to determine the impact of key design parameters on both energy and exergy efficiencies. The optimal values must balance exergy destroyed due to heat transfer and exergy destroyed due to pressure losses, which have competing effects. Optimization is utilized to determine parameter values within a feasible design window, which leads to a maximum exergetic efficiency of 87%.

Keywords: Thermal energy storage; Exergy analysis; Multi-phase; Optimization

1. Introduction

Thermal energy storage (TES) has been identified as one of the primary solutions to increase utilization of solar energy to bridge the gap between solar availability and peak demand, enable higher capacity factor, and permit flexible dispatchability in solar thermal power plants (STPP) Department of Energy, 2012. This paper addresses a proposed single-tank TES system utilizing fluids in their two-phase (liquid–vapor) to supercritical states. In particular, it characterizes the thermodynamic performance of such a system during a full working cycle and explores the sensitivity of first- and second-law efficiencies to key design parameters (mass flow rate, tube geometry, operating temperature).

Current commercially deployed thermal storage systems in parabolic trough STPPs are two-tank sensible heat designs using molten salt as the storage medium (Bradshaw et al., 2009; Herrmann et al., 2004). The most substantial challenge of this technology is its high capital cost at \$80/kW h_t (SunShot, 2012). Currently, the TES system operates with a small temperature difference between the hot tank (at 400 °C) and the cold tank (at 300 °C). The principal objective of the larger study undertaken in our group (Ganapathi and Wirz, 2012) is to investigate low-cost storage media options by considering operation at higher pressures typically found in the two-phase and supercritical regimes. By thermally cycling the storage fluid across a large temperature differential, the excursion in

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http://dx.doi.org/10.1016/j.solener.2015.08.026
0038-092X/

Nomenclature

A	cross-sectional area (m^2)
c	specific heat of fluid ($J\ kg^{-1}\ K^{-1}$)
E	energy (J)
Ex	exergy (J)
f	friction factor
h	heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
k	thermal conductivity ($Wm^{-1}\ K^{-1}$)
m	storage fluid mass (kg)
$\dot{m}$	HTF mass flow rate ($kg\ s^{-1}$)
N_L	number of tube rows
P	pressure (kPa)
P_h	heat transfer perimeter (m)
q	heat rate (W)
T	cross-sectional average temperature (°C)
u	internal energy per unit mass ($J\ kg^{-1}$)
V	HTF velocity (m/s)
x	distance through the tank (m)
χ	correction factor
η	pump efficiency
ρ	fluid average density ($kg\ m^{-3}$)
ψ	exergetic efficiency
CSP	concentrating solar power
HTF	heat transfer fluid
STPP	solar thermal power plant
TES	thermal energy storage

Subscripts

b	bypass
c	critical
charge	charging period
discharge	discharging period
gen	generator
i	inner
in	inlet
max	maximum
o	outer
out	outlet
sol	solar field
stor	storage
tank	tank (refers to HTF flow through tank)
tot	total
wall	wall (refers to wall of tube containing storage fluid)

internal energy can access both sensible heat and latent heat of vaporization. The main challenge to such a system is the high pressure associated with the high temperature state, necessitating a thick-walled storage vessel. To mitigate this cost, the proposed design utilizes a single-tank TES system, effectively halving the required wall material.

Exergy analysis has become a fundamental approach in analyzing the thermodynamic performance of a wide variety of TES systems. While energy analysis is based on the First Law of Thermodynamics and provides information about the quantity of energy, exergy analysis is based on the second Law of Thermodynamics and considers the quality of energy, which helps determine where available energy is inefficiently used. In fact, the utility of exergy methods are becoming more widely recognized in recent years. There have been many studies that utilize exergy analysis for TES performance evaluation, including PCM systems (Domański and Fellah, 1995, 1996; Jegadheeswaran et al., 2010; Koca et al., 2008; Kousksou et al., 2007; Ramayya and Ramesh, 1998; Shabgard et al., 2012; Tse et al., 2014), sensible heat storage (Jegadheeswaran and Pohekar, 2010; Mawire et al., 2008; Rosen et al., 1988; Rosen, 2001), and thermochemical systems (Dincer and Rosen, 2002; Kreetz and Lovegrove, 2002; Lovegrove et al., 1999). However, there exists a wide range of approaches, and some have concluded that a standard convention is required in order to fairly assess TES performance (Dincer and Rosen, 2002; Rosen, 1992; Rosen and Dincer, 2003). The rationale is that the energy efficiency of a TES system has remained the primary metric for overall performance, but can be an inadequate measure because it does not take into account all considerations necessary in TES evaluation (e.g., temperatures of the supplied and recovered energy, storage duration, and how nearly the system approaches ideal performance).

Previous researchers have investigated optimum specifications for key parameters in designing a wide range of TES systems (Forristall, 2003; Patnode, 2006; Newbery, 2004; Price, 2003). Pioneering works by Bejan (Bejan, 1978, 1980, 1988) utilized exergy analysis to evaluate the performance of a sensible heat storage (SHS) system and identify an optimum charging time and an optimum number of thermal units. Other studies have extended Bejan's analysis by modeling the entire charge–discharge cycle and concluded that a typical optimized system destroyed about 70–90% of the supplied exergy content, as reported by Krane (1987) and Domański and Fellah (1998). Aceves-Saborio et al. (1994) presented a versatile lumped model for characterizing latent heat storage systems, with emphasis on the potential for a wide range of applications. In Rosen's work (Rosen, 2001), the importance of modeling spatial variations of temperature in TES systems is demonstrated. Dincer and Rosen (2002), Dincer et al. (1997) investigated the viability of different SHS media and defined useful criteria for evaluating exergetic performance. Gunnewiek et al. (1993) studied the optimum