Applied Energy 228 (2018) 240–253

Contents lists available at ScienceDirect

Applied Energy

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

Cyclic performance of cascaded and multi-layered solid-PCM shell-and-tube thermal energy storage systems: A case study of the 19.9 MW$_e$ Gemasolar CSP plant

S. Saeed Mostafavi Tehrani[a,*], Yashar Shoraka[a], Karthik Nithyanandam[b], Robert A. Taylor[a]

[a] *School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, NSW 2052, Australia*
[b] *Department of Mechanical Engineering, University of California, Los Angeles, CA 90095, USA*

HIGHLIGHTS

- The melting point selection of cascaded systems is the most crucial design consideration.
- The true potential of cascaded designs can only be realized with annual cyclic analysis.
- A design with 50% concrete in the middle and 25% PCMs at each end performed best.
- CSP off-design operation is required for comparable performance of alternative TES systems.

ARTICLE INFO

Keywords:
Cascade
Phase change material
Concrete
Thermal energy storage
Shell and tube

ABSTRACT

A shell-and-tube heat exchanger which incorporates a sensible or phase change material (PCM) as the storage medium offers a potentially commercially viable alternative to the two-tank molten salt system. In particular, cascaded PCMs and multi-layered solid-PCMs (MLSPCMs) were investigated as proposed systems which can reduce the amount of storage material used and ensure optimal storage utilization. In this work, the performance of various thermal energy storage (TES) alternatives integrated into the 19.9 MW$_e$ Gemasolar concentrated solar power (CSP) plant (located in Seville, Spain) were compared with the conventional two-tank system. These alternative storage configurations were characterized by a single tank filled with a single, cascaded, or multi-layered storage media. Importantly, as a system-level study, this paper compared the performance of the design alternatives integrated with other CSP components in order to capture the effect of dynamic interactions between the storage system and other CSP components. Through a validated numerical investigation of the annual performance of the integrated systems, all the design alternatives were compared in the context of annual electricity generation, which represents the ultimate criterion to judge the true potential of each alternative. To conduct an apples-to-apples comparison, the storage capacity and geometric parameters were fixed. The design alternatives were categorized based on the storage materials involved and their percentages of occupancy in the TES tank (i.e. 12 storage groups and a total number of 45 design alternatives). It was found that the well-designed TES designs with cascaded PCMs performed similarly in charging and discharging (i.e. with a similar amount of total stored or delivered energy per cycle). This contrasts with a single PCM system, where there exists a significant difference between charging and discharging performance. The results of annual cyclic performance, under real-time operational conditions, indicated that a MLSPCM design configuration that was filled with a high melting point PCM in the top 25% of the tank, sensible concrete in the middle 50%, and a low melting point PCM in the bottom 25% of the tank had the best performance among all design alternatives studied. Moreover, it was found that changing the filler portions any one cascaded PCM group cannot significantly change the *annual* performance of the system. Contrary to much of the available literature – literature which does not consider system integration – it was shown that the shell-and-tube alternatives can only *approach* the annual performance of two-tank systems under 'extended' operational conditions (i.e. allowing temperature set points to float relatively far away from their fixed design points).

---

* Corresponding author.
E-mail addresses: s.mostafavi.tehrani@gmail.com (S.S. Mostafavi Tehrani), yshoraka@gmail.com (Y. Shoraka), kartn87@ucla.edu (K. Nithyanandam), robert.taylor@unsw.edu.au (R.A. Taylor).

https://doi.org/10.1016/j.apenergy.2018.06.084
Received 8 March 2018; Received in revised form 24 May 2018; Accepted 17 June 2018

Nomenclature

b	tube thickness [m]
C_P	specific heat at constant pressure [J/kg K]
D	outer diameter of storage unit [m]
d	diameter of tube or filler [m]
f_l	liquid fraction [–]
h	convective heat transfer coefficient [W/m^2 K]
h_{sl} or ΔH	latent heat of fusion [J/kg]
k	thermal conductivity [W/m K]
L	length or height of tank [m]
$\dot{m}$	mass flow rate [kg/s]
N_p	number of latent heat storage modules (pipes) [–]
Q	amount of stored/discharged energy [J]
$\dot{Q}$	rate of stored/discharged energy [W]
R	outer radius of a cylinder or filler radius [m]
Re	Reynolds number [–]
r_o	inner radius of pipe [m]
t	total time of simulation [s]
T	temperature [K]
T_{m1}	solidus temperature [K]
T_{m2}	liquids temperature [K]
V	volume [m^3]
v	velocity [m/s]
$\dot{W}$	work (electrical power) [W]

Greek symbols

ρ	density [kg/m^3]
μ	dynamic viscosity [kg/m s]
ε	porosity [–]

Subscripts

F	filler
HTF	solar salt fluid (heat transfer fluid)
In	inlet
M	melting
out	outlet
R	radial direction
rec	receiver
Z	axial direction
W	wall

Abbreviations

CSP	concentrated solar power
HTF	heat transfer fluid
PB	power block (the Rankine cycle)
MLSPCM	multi-layered solid-PCM
PCM	phase change material
SMT	single medium thermocline
TES	thermal energy storage

1. Introduction

Concentrated solar power (CSP) plants can be coupled with cost-effective thermal energy storage (TES) systems to minimize the mismatch between power generation and demand/consumption [1,2]. While there are many technical solutions for the solar field, the receiver, the working fluid, and other components, the sole commercial TES example is the two-tank storage system using molten salts – a technology which has been deployed in many CSP plants, including the 19.9 MW$_e$ Gemasolar CSP-tower plant in Spain [3,4]. While this method of storage has indeed served its purpose, the storage cost must be considerably reduced going forward to make CSP economically competitive [5]. Furthermore, due to environmental and health considerations, reducing the amount of molten salts used is beneficial [6]. Developments in the field of advanced TES systems for CSP mainly include searches for better storage materials [7], investigations into new operational modes [8], and exploration of novel, potentially more efficient, configurations [9].

TES systems can be classified into three broad categories [3,5]: (1) sensible systems, in which solid and/or liquid media are used, (2) latent heat systems, which embody phase change materials (PCM), and (3) thermochemical storage systems, wherein reversible thermochemical reactions are used. The current study is focused on comparing the first and second categories, which are the most promising near-term options for TES systems. In particular, this study focusses on TES systems that incorporate multiple PCMs – cascaded or multistage designs. In these systems, different types of phase change materials (PCM) with different melting temperatures, specific heat capacities, and latent heats of fusion are optimally arranged in series in order to enhance the overall heat transfer performance of the system [10]. In addition to these, systems which use PCM layers in concert with sensible materials (e.g. concrete), called a 'multi-layered solid-PCM' design, were also studied, since they have been reported to be advantageous in recent publications [11,12].

As explained in [10,13,14], the heat transfer rate in a TES system depends on the temperature difference between the HTF and the PCM. Therefore, if various PCMs are arranged in a decreasing order of their melting points from the hot HTF inlet, a nearly constant temperature difference (and a uniform heat transfer rate) can be maintained along the flow direction. Otherwise, if a single PCM configuration is used, the temperature difference between the PCM and the HTF decreases along the flow direction, which also decreases the heat transfer rate. Farid and Kanzawa quantified an increase up to 10% (numerically) and 15% (experimentally) during the latent heat operating regime of a packed bed system when multiple PCMs were incorporated [15,16]. Moreover, this increase in the heat transfer rate can also lead to a reduction in the required volume and mass of the storage system, which consequently results in an economic savings [17]. As compared to single PCM systems, cascade/multi-layer PCM systems have also been reported to have a longer period of uniform outlet HTF temperature during the charging and discharging processes [18,19], a reduction in the required charging and discharging time [19,20], and an increase in exergy efficiency [21], along with a few other important operational advantages.

Dual-media thermocline (DMT) and shell-and-tube (ST) systems, are the two most commonly proposed configurations for incorporating sensible and latent heat storage materials into the TES system of a CSP plant [22–24]. The focus of this study is on the shell-and-tube design due to its lower complexity and forecasted storage costs compared to encapsulated PCM systems [24]. In shell-and-tube configurations, the heat transfer fluid (HTF) and PCM are physically separated by a metal tube, with the PCMs typically located in the shell region [25]. High-temperature shell-and-tube PCM storage has recently been studied by the co-authors, in Tehrani et al. [23]. It was shown that geometric optimization of the design can substantially impact its viability, and that each particular design has an optimum surface area beyond which diminishing heat transfer performance returns are expected. The key parameters involved in geometric optimizations are tank height (L), the shell to tube radius ratio (R/r_o), the length to tube diameter ratio (L/d), and the number of pipes (N_p).