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Performance investigation of a lab-scale latent heat storage prototype – Experimental results

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ABSTRACT

This paper presents the performance tests carried out on a lab-scale latent heat storage (LHS) prototype during charging and discharging processes. The storage unit is a shell-and-tube type heat exchanger with embedded finned tubes, designed for an LHS capacity of 10 MJ. A ternary mixture comprising of potassium nitrate, sodium nitrate and sodium nitrite in the weight proportion of 53:7:40 is used as the phase change material (PCM). Hi-Tech Therm 60 is used as the heat transfer fluid (HTF). Performance parameters viz., melt fraction, charging/discharging time and energy storage/discharge rate were evaluated at different operating conditions. The effects of HTF inlet temperature and flow rate on the storage characteristics of LHS prototype were analyzed. It is observed that the temperature variation in the angular direction of the prototype during charging process is significant. This is due to the natural convection heat transfer that occurred around the molten layer of PCM while melting. During the discharging process, the angular temperature variation is negligible as the solidification phenomenon is controlled mainly by the conduction heat transfer. It took about 124 min/131 min for charging/discharging of the LHS prototype.

1. Introduction

A major advantage of concentrated solar power (CSP) plants over solar PV plants is the ability to integrate the cost-effective thermal energy storage (TES) for improved dispatchability and reliability. Cabeza et al. (2015), Dincer and Rosen (2002), Hasnain (1998) and Kuravi et al. (2013) discussed in detail about the various aspects of TES technologies and their applications for CSP plants. Several researchers have investigated the performance of TES systems of different configurations (Liu et al., 2006; Merlin et al., 2016; Trp, 2005). Though several prototypes of TES were developed across the world, only a few large-scale TES systems have been commissioned in the CSP plants (Gil et al., 2010).

TES systems can be broadly classified into sensible heat storage (SHS), latent heat storage (LHS) and thermochemical heat storage (THS) systems. LHS systems using phase change materials (PCMs) are highly attractive due to their high volumetric heat storage capacity, compactness, moderate cost and near constant temperature heat storage/retrieval. Steinmann and Eck (2006) studied various buffer storage options for direct steam generation solar power plant. They found that the integration of LHS system allows an increase in volumetric storage capacity of the steam accumulators and reduces the decline in pressure of the steam during the discharge process. Extensive reviews on the materials, heat transfer analysis and applications of LHS systems are reported in the literature (Anisur et al., 2013; Kenisarin and Mahkamov, 2007; Khan et al., 2016; Sharma et al., 2009; Zalba et al., 2003).

In general, the LHS system consists of a regenerator type heat exchanger wherein the heat transfer fluid (HTF) passes through the storage media for charging and discharging only. During charging, the high-temperature HTF transfers heat to the storage medium. The stored energy is released during discharging as the low-temperature HTF passes through it. Zhang et al. (1993) conducted several experiments to study the melting characteristics of *n*-octadecane kept in a rectangular enclosure. One side of the rectangular enclosure was discretely heated at a constant flux, and the remaining sides were maintained at adiabatic conditions. They found that the temperature in the upper region of the enclosure was higher than that of the lower region during the melting process. It was due to the natural convection heat transfer, which was developed after the formation of molten PCM. On the contrary, the solidification process is mainly by conduction heat transfer. Sari and Kaygusuz (2002) experimentally studied the heat transfer characteristics of lauric acid in a shell-and-tube LHS system during melting and solidification. They reported that the solidification process was controlled by heat conduction and it was slowed

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Nomenclature

b	fin thickness (m)
C_p	specific heat (J kg^{-1} °C^{-1})
C_{ps}	specific heat of the solid PCM (J kg^{-1} °C^{-1})
C_{pl}	specific heat of the liquid PCM (J kg^{-1} °C^{-1})
D	inner diameter of prototype (m)
d	outer diameter of HTF tubes (m)
$E_{L,C}$	latent energy stored during charging (J)
$E_{L,D}$	latent energy discharged during discharging (J)
$E_{S,C}$	sensible energy stored during charging (J)
$E_{S,D}$	sensible energy discharged during discharging (J)
$E_{T,C}$	total energy stored during charging (J)
$E_{T,D}$	total energy discharged during discharging (J)
h	fin height (m)
k	thermal conductivity (W m^{-1} °C^{-1})
L	PCM filled length of prototype (m)
L_F	latent heat of fusion (J kg^{-1})
m	mass (kg)
N_T	number of HTF tubes
N_F	number of fins
Q	amount of heat (J)
T	temperature (°C)
T_M	phase change temperature (°C)
t	time (s)
V	volume (m^3)

ΔT_M	semi – mushy zone

Greek symbols

ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)
γ	kinematic viscosity (m^2 s^{-1})
θ	melt fraction

Subscripts

ini	initial
L	liquidus
S	solidus

Abbreviations

CSP	concentrated solar power
HTF	heat transfer fluid
LHS	latent heat storage
PCM	phase change material
PV	photovoltaic
SHS	sensible heat storage
TES	thermal energy storage
THS	thermochemical heat storage

due to the conduction thermal resistance of the solidified layer, which gets formed around the HTF tube.

The most intensely studied LHS system among various configurations is the shell-and-tube system. More than 70% of the published research on LHS system reported shell-and-tube configuration (Agyenim et al., 2010b). In the shell-and-tube configuration, PCM is usually filled in the shell, and the HTF flows through the tubes. Avci and Yazici (2013) performed an experimental study for evaluating TES characteristics of paraffin in a horizontal shell-and-tube storage unit. They found that the temperature field is radially uneven during the melting process in the horizontal annulus due to natural convection. Trp et al. (2006) studied the storage phenomenon during melting and solidification of paraffin in a vertical shell-and-tube LHS storage unit. They reported that the temperature distribution in the PCM is non-isothermal during melting and isothermal during solidification. Hosseini et al. (2014) performed an experimental and numerical study to understand the role of buoyancy driven convection during melting and solidification of PCMs in a horizontal shell-and-tube storage unit. They found that the buoyancy-driven convection is dominant during the charging process and negligible during the discharging process. Agyenim et al. (2010a) experimentally studied the effect of using multiple HTF tubes in shell-and-tube LHS units. The multi-tube system showed superior performance than the single tube system aided with the distribution of heat in multiple layers around each HTF tube to the PCM. Certain numerical studies also portrayed the advantages of using multiple tubes in LHS systems. Esapour et al. (2016) developed a 2D numerical model to study the influence of the number of HTF tubes in an LHS system during the charging process. They reported that by increasing the number of HTF tubes, the bottom region of the shell is influenced by the additional heat transfer surface thereby reducing the total melting time by about 29% for the four tubes system. In a more recent experimental work by Allouche et al. (2015), the performance of a microencapsulated PCM in a tube-bundle heat exchanger for low-temperature TES was studied. When compared the results with previously published results for other configurations, the tube-bundle storage tank configuration was found to perform better than a coil-in-tank configuration. They also mentioned that shell-and-tube type of heat exchanger has the additional advantage of incorporating fins to the HTF tubes, which can significantly enhance the heat transfer.

Arrangement and orientation of HTF tubes and fins also have an impact on the performance of LHS system. Symmetric configuration is generally recommended for better performance. Yazici et al. (2014a,b) experimentally studied the effect of eccentric placing of HTF tube in a horizontal shell-and-tube LHS system. They found a decrease in charging time due to the enhancement of natural convection. But the discharging time was considerably increased due to the increase in conduction resistance. Seddegh et al. (2016) compared the performances of horizontal and vertical shell-and-tube LHS systems. They concluded that the horizontal LHS system showed a better storage performance during the charging process and no notable difference was found between the two systems during the discharging process.

Low thermal conductivity of PCMs is a limiting performance parameter for the PCM based LHS, and it necessitates heat transfer enhancement techniques like adding fins, graphite flakes and sprinkling high thermal conductivity micro/nano particles (Fan and Khodadadi, 2011; Jegadheeswaran and Pohekar, 2009). Sparrow et al. (1981) conducted several experiments on freezing of PCM with finned and unfinned cold tubes. They showed that the usage of fins could triple the amount of PCM that freezes around a cold tube. Choi and Kim (1992) conducted an experiment to investigate LHS characteristics of magnesium chloride hexahydrate for TES. They compared the heat transfer coefficients with finned and unfinned tube systems and found its ratio to be 3.5 for the geometry investigated. Zhai et al. (2015) investigated the influence of fin in a shell-and-tube type cold LHS system. They used 4 annular and 4 longitudinal fins that divided the storage system into 20 pockets of PCM. The results showed that the phase change time for the finned unit decreased by about 71.2% com-