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Impact of the heat transfer fluid in a flat plate phase change thermal storage unit for concentrated solar tower plants

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Abstract

Thermal energy storage allows improved dispatch-ability of power from a concentrated solar power plant and increases its annual capacity factor. The selection of an appropriate heat transfer fluid (HTF) is important for designing a cost-effective thermal storage system and to improve the cycle efficiency of the power plant. The current state-of-the-art HTF for tower power plants is molten salts, which have the drawback of having low degradation temperature and high melting temperatures respectively. Alternative HTFs under investigation allow for a much larger range of operation, and can offer other cost and performance advantages. In this study, a comparison of six gaseous and liquid HTFs was carried out to determine their suitability for use in a high temperature thermal storage unit with flat slabs of phase change materials. The comparison is in terms of their thermo-physical properties, heat transfer characteristics between the flat plates and the total delivered electrical energy to the grid. Using a validated mathematical model of phase change material in thin slabs, the HTF outlet temperature, heat transfer rate and liquid fraction profiles were predicted when using different HTFs at a constant heat capacity rate for both charging and discharging processes. For the capacity rate considered, liquid sodium was identified as the best HTF, delivering the highest electrical energy to the grid, achieving 99.4% relative to the ideal case. Solar salt achieved a value of 93.6%, while the gaseous fluids of atmospheric air, air at 10 bar, s-CO_2 at 100 bar and steam at 10 bar achieved between 87.9% and 91.3% of the ideal delivered electricity. Gaseous fluids have the advantage of being able to be used as the working fluid in the power block. This study shows that gaseous fluids are comparable to liquid HTFs in PCM storage facilities.

Keywords: Heat transfer fluid; Phase change material; Thermal energy storage; Solar thermal; Solar tower

1. Introduction

Concentrated solar power (CSP) with thermal storage is becoming the renewable energy of choice to replace conventional power stations. Current thinking suggests that solar power towers will be the cheapest CSP technology in 2020 (Sargent and Lundy LLC Consulting Group, 2003). Thermal energy storage solves the time mismatch between solar energy supply and electricity demand. The state-of-the-art thermal energy storage in tower power plants are two-tank direct sensible storage using molten salt made of 60 wt.% $NaNO_3$ and 40 wt.% KNO_3 (Kuravi et al., 2013). Fig. 1 presents a schematic of a solar tower power plant with a two-tank molten salt storage (Carlqvist, 2009). In the charging process, cold molten salt is pumped from a cold storage tank (290 °C) through the central receiver, where it is heated up to 565 °C and then stored in a hot tank. When the stored energy is needed, the hot molten salt is pumped to a steam generating system that produces superheated steam at nominal conditions of 540 °C and

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Abbreviations: Heat transfer fluid, HTF; Phase change materials, PCMs; Phase change thermal storage unit, PCTSU; Supercritical CO_2, s-CO_2.

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Nomenclature

c_p	specific heat (kJ/kg K)	Re	Reynolds number (–)
g	gap width between two slabs (m)	$T_{s,c}$, $T_{s,d}$	source temperatures in charging and discharging (°C)
h	heat transfer coefficient of the HTF (W/m^2 K)	T_m	phase change temperature (°C)
H	half of the slab thickness (m)	T_L	low temperature (K)
k	thermal conductivity of the PCM (W/m K)	T_H	high temperature (K)
k_f	thermal conductivity of the HTF (W/m K)	v	HTF velocity (m/s)
$dotm$	mass flow rate of the HTF (kg/s)	V	PCM volume in the storage unit (m^3)
Nu	Nusselt number (–)	$dotV$	volumetric flow rate of the HTF (m^3/s)
P_g	power to the grid (MW)	ΔH	latent heat energy of the PCM (kJ/kg)
P_e	electrical power (MW)	ΔP	pressure drop in the PCTSU (Pa)
P_L	pumping loss (kW)	μ	dynamic viscosity (Pa s)
Pr	Prandtl number (–)	f	friction factor (–)
Q	energy stored in the PCM of volume V (kJ)	η_p	pump efficiency (–)
Q_{ideal}	ideal delivered electrical energy to the grid (MW h)	η_{ps}	power station efficiency (–)
Q_{act}	actual delivered electrical energy to the grid (MW h)	η_{ratio}	efficiency ratio (–)
$q_{\text{discharge}}$	discharging thermal energy from the PCTSU (MW)	ρ	density (kg/m^3)

125 bar for a two-stage Rankine-cycle turbine. Then the cold molten salt is returned from the steam generator at 290 °C and stored in the cold tank. To realize a discharge duration of 6 h for a 50 MW power plant, approximately 7300 ton (3900 m^3) $NaNO_3/KNO_3$ molten salt is required. The properties of $NaNO_3/KNO_3$ molten salt were obtained from the Solar Adviser Model (NREL, 2009).

Compared with the state-of-the-art sensible energy storage, phase change materials (PCMs) have the advantage of potentially storing more energy per unit volume, achieving a lower cost per unit of stored energy (Gil et al., 2010). Phase change thermal storage has been applied in numerous low temperature applications and is a very promising technology for high temperature thermal storage in concentrated solar power applications. When solar radiation is available, the heat energy obtained from the solar receiver by the HTF can be stored in the PCM by changing the phase of the PCM from solid to liquid, which is called the charging process. Later on, when there is higher electricity demand or tariffs or during cloudy periods, the stored heat can be recovered and used for steam generation. During the discharging process, the PCM freezes, transferring the stored energy to the HTF.

Flat plate phase change thermal storage unit (PCTSU) is one of the popular configurations currently in use and it has been studied by many researchers (Morrison and Abdel-Khalik, 1978; Ismail et al., 1999a, Zalba et al., 2004; Saman et al., 2005; Dolado et al., 2011; Liu et al., 2012a). A significant drawback of PCMs is the low thermal conductivity, and considerable work has been undertaken to increase conductivity (Tamme, 2007; Pincemin et al., 2008; Steinmann et al., 2009; Shabgard et al., 2010). The configuration of PCM encapsulation in thin flat slab achieves a higher ratio of heat transfer surface to PCM volume compared to other encapsulations such as spheres, reducing the thermal resistance between the HTF and the PCM across the thickness of the slab. Consequently, the heat transfer is dominated by the convection heat transfer defined by the HTF and selecting the optimum HTF is critical for the charging/discharging rate of the storage system.

Molten salts have been used as both a HTF and a storage medium in Solar Tres power tower solar power plants (Liu et al., 2012b). The solar field outlet temperature is above 550 °C. Molten salts present excellent thermal properties at higher temperatures, such as high density, high heat capacity, low viscosity and high thermal conductivity. Moreover, they are thermally stable, non-flammable, nontoxic and can be operated under ambient pressure. There are a few commercially available molten salts. One is a binary eutectic nitrate salt consisting of 60% $NaNO_3$ and 40% KNO_3, namely solar salt. Another developed molten salt is Hitec, which is made of 53% KNO_3, 40% $NaNO_2$ and 7% $NaNO_3$. The maximum operation temperatures of solar salt and Hitec are 585 °C and 535 °C, respectively. The disadvantage of molten salts as HTFs is their high melting point (221 °C for solar salt and 142 °C for Hitec). Therefore, costly freeze protection is required.

Liquid metal such as liquid sodium has a lower melting point of 97.7 °C and a higher boiling point of 873 °C than molten salts, resulting in a larger system operation temperature. The major disadvantage of sodium is its reaction