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A cost and performance comparison of packed bed and structured thermocline thermal energy storage systems

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Abstract

A structured concrete thermocline thermal energy storage (TES) system is proposed as an alternative to currently-used TES systems. The issues of material settlement and thermal ratcheting found in packed bed thermocline TES systems is avoided by replacing the packed aggregate bed with structured high-temperature concrete. A summary of all utility scale TES systems with integrated TES in existence today is provided and discussed. Cost reduction options such as replacing two-tank systems with single-tank systems and replacing liquid storage media with solid storage media are discussed along with limitations of both options. Numeric models are developed to simulate the performance of utility scale packed bed and structured thermocline TES systems; efficiencies of 92.37% and 84% are modeled for packed-bed and structured systems. A complete cost analysis of utility-scale, 2165 MWh packed bed and structured systems is conducted; capacity costs of $30/kWh and $34/kWh are determined for packed bed and structured systems respectively. A structured concrete thermocline is deemed to be a viable TES option due to its low cost and the fact that there are no concerns of thermal ratcheting of the tank.

Keywords: Solar energy; Thermal energy storage; Thermocline; Molten salt; Cost analysis

1. Introduction

Increasing global energy demands and diminishing fossil fuel resources have raised interest in renewable energy resources. Sufficient solar irradiance is incident on the Earth's surface to fuel the production of electrical energy for all of its inhabitants (Goswami et al., 2000). However, efficient and reliable methods of harvesting solar energy for power production are needed. Solar energy is harvested and converted to electrical energy using one of two technologies: photovoltaic (PV) panels or concentrating solar power (CSP) plants.

PV panels convert solar energy to electric energy directly; this method of conversion is mature, scalable, and relatively low cost: $4740/kW for utility installments (>100 kW) (Feldman et al., 2012). Two primary drawbacks are associated with PV: electric power output is subject to rapid fluctuations and is only available when the sun is shining. Considering the first drawback, power production can rapidly shift from peak to minimal and back to peak as clouds drift in front of the sun. It is challenging and costly to design control systems and backup generators capable of responding to these fluctuations rapidly enough to maintain a steady supply of power to the grid (Denholm and Mehos, 2011). Considering the second drawback, since PV panels convert solar energy directly to electrical energy, it follows that electricity can only be produced when the

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Nomenclature

α	thermal diffusivity (m^2/s)
Bi	Biot number, hL_c/k (dim)
c_p	specific heat at constant pressure (J/kg °C)
d	bed particle diameter (m)
D_y	node spacing in PBTC model (m)
D_h	hydraulic diameter (m)
ε	porosity (dim)
h	convection coefficient (W/m^2 °C)
h_v	volumetric convection coefficient (W/m^3 °C)
k	thermal conductivity (W/m °C)
k_1,k_2	empirical coefficients associated with the Ergun equation (dim)
L	length of concrete plate or packed bed (m)
L_c	characteristic length, d/6 for sphere (m)
$\dot{m}$	fluid mass flow rate (kg/s)
ρ	density (kg/m^3)
P	wetted perimeter (m)
ΔP	pressure drop (Pa)
R_i	inner radius (half of fluid channel thickness) (m)
R_o	outer radius (half of fluid channel thickness plus axisymmetric element wall thickness) (m)
S	cross-sectional area of fluid flow channel (m^2)
t	time (s)
T	temperature (°C)
T_i	thickness of fluid flow channel (m)
T_o	thickness of fluid flow channel plus thickness of concrete plate (m)
υ	kinematic viscosity (m^2/s)
V	bulk fluid velocity (m/s)
Φ	empirical coefficient associated with the Ergun equation (dim)

Subscripts

F	fluid
M	material

Acronyms

CSP	concentrating solar power
DTC	direct thermocline
HTF	heat transfer fluid
PBTC	packed-bed thermocline
PV	photovoltaic
SCTC	structured-concrete thermocline
TES	thermal energy storage
TTI	two-tank indirect

sun is shining. Unfortunately, times of peak power demand (shortly after sunset) do not coincide with periods of peak irradiance; though excess electrical energy can be produced during the day and utilized during evening hours, the high cost of large-scale electrical energy storage is not viable (Table 1).

Though CSP is a younger and more costly conversion technology, approximately \$5500/kW for utility installments (>50 kW) (Feldman et al., 2012), it is a more viable option than PV at the utility scale because CSP plants can be easily integrated with thermal energy storage (TES). Excess solar energy can be collected and stored as thermal energy. This energy can then be dispatched at will for conversion to electrical energy in a traditional Rankine steam power cycle. This effective "thermal battery" allows the plant to continue power production well into the hours of peak demand after sunset.

Table 1
Energy storage concepts and costs (Schoenung, 2011; EPRI, 2010; Medrano et al., 2010).

Energy storage Concept	Capacity cost (\$/kWh)	Efficiency (%)
Sealed lead acid battery	\$333.00	80.00
Lithium ion battery	\$600.00	85.00
Super capacitor	\$10,000.00	95.00
High speed flywheel	\$1600.00	95.00
Pumped hydro	\$75.00	85.00
Two-tank indirect	\$89.00	97.00
Two-tank direct	\$50.00	97.00
Packed-bed thermocline	\$34.00	93.00

A summary of all CSP plants with integrated TES that are in operation or are under construction is provided in Table 2 (NREL, 2014). From this list, it can be seen that the current standard in TES is the two-tank indirect (TTI) configuration with nitrate salt as the energy storage media, and the operating temperature range of 290–390 °C. Fig. 1A illustrates the TTI TES system configuration and a parabolic trough solar collector field. Solar energy is collected in the solar field, where parabolic troughs focus irradiance on receivers, through which thermal oil heat transfer fluid (HTF) is circulated. The oil is then circulated to an oil-to-salt heat exchanger, where the collected energy is transferred to nitrate salt. Heated salt is stored in a "hot" tank until the energy is dispatched, at which point the oil and salt are circulated through a salt-to-oil heat exchange. The hot oil then circulates to the power block and the "cold" salt is stored in the "cold" tank until it is re-heated.

Salt is utilized as energy storage media primarily because it is much more cost-effective than using thermal oil as storage media. To put this in perspective, the thermal mass of solar salt ($\rho \cdot c_p$) of solar salt and Therminol VP-1 (thermal oil) are relatively comparable at 2.485 MW/m^3 °C and 1.865 MW/m^3 °C (Van Lew et al., 2011). However, the difference in operating temperature differentials of the two fluids is significant, at 275 °C and 100 °C respectively. This means that on a volumetric basis, solar salt has 3.664 times