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System-level simulation of a solar power tower plant with thermocline thermal energy storage

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HIGHLIGHTS

- Molten-salt thermocline tanks offer low-cost thermal energy storage for concentrating solar power plants.
- A new thermocline tank model is developed to provide comprehensive thermal simulation at low computational cost.
- The thermocline model is incorporated into a system model to study storage performance over long-term plant operation.
- Yearlong simulation of a power tower plant indicates excellent storage performance with the thermocline tank concept.

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ABSTRACT

A thermocline tank is a low-cost thermal energy storage subsystem for concentrating solar power plants that typically utilizes molten salt and quartzite rock as storage media. Long-term thermal stability of the storage concept remains a design concern. A new model is developed to provide comprehensive simulation of thermocline tank operation at low computational cost, addressing deficiencies with previous models in the literature. The proposed model is then incorporated into a system-level model of a 100 MW_e power tower plant to investigate storage performance during long-term operation. Solar irradiance data, taken from measurements for the year 1977 near Barstow, CA, are used as inputs to the simulation. The heliostat field and solar receiver are designed with DELSOL, while the transient receiver performance is simulated with SOLERGY. A meteorological year of plant simulation with a 6-h capacity for the thermocline tank storage yields an annual plant capacity factor of 0.531. The effectiveness of the thermocline tank at storing and delivering heat is sustained above 99% throughout the year, indicating that thermal stratification inside the tank is successfully maintained under realistic operating conditions. Despite its good thermal performance, structural stability of the thermocline tank remains a concern due to the large thermal expansion of the internal quartzite rock at elevated molten-salt temperatures, and requires further investigation.

1. Introduction

Concentrating solar power (CSP) exploits the conversion of direct sunlight to high-temperature heat for large-scale power production. While it is a sustainable and environmentally benign source of energy, sunlight is an intermittent resource whose intensity is subject to planetary rotation, orbit, and atmospheric effects associated with weather conditions. Commercial facilities must therefore decouple solar collection from power production to meet consumer demand, independent of the prevailing conditions of solar irradiance. The generation of high-temperature heat in CSP plants provides built-in potential for the use of thermal energy storage systems to achieve this decoupling. While several design concepts exist for thermal energy storage, commercial storage systems must exhibit low cost, reliability, and effective delivery of heat for power production.

Thermal storage mechanisms involve sensible heat, latent heat, or thermochemical reactions. Sensible heat-based systems offer low energy densities but enable direct integration into the solar collection flow loop, avoiding rate-limiting steps inherent to the alternative phase-change or reaction-based approaches. Application of sensible storage is also practical for traditional Rankine cycles, where heat addition to the working fluid occurs across a temperature rise. Current CSP plants featuring thermal energy storage therefore apply a sensible heat-based concept known as two-tank storage. In the case of a power tower plant employing this storage system, hot fluid (*e.g.*, molten salt) exits the solar receiver during daylight and flows to a nominally isothermal hot tank. When power

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Nomenclature

Bi	Biot number, $\mathrm{Bi} = \frac{\mathrm{Nu}_i}{36(1-\varepsilon)}\frac{k_l}{k_s}$
C_p	specific heat, J/kg-K
d	solid filler size, m
E	liquid heel energy, J
h	enthalpy, J/kg
h_i	interstitial heat transfer coefficient, W/m^3-K
k	thermal conductivity, W/m-K
$\dot{m}$	mass flow rate, kg/s
M	liquid heel mass, kg
N	turbine blade speed, rpm
Nu_i	Nusselt number, $\mathrm{Nu}_i = \frac{h_i d^2}{k_l}$
p	pressure, Pa
Pr	Prandtl number, $\mathrm{Pr} = \frac{C_{p,l}\mu_l}{k_l}$
P_{rec}	receiver power, W
r	tank wall radius, m
Re	Reynolds number, $\mathrm{Re} = \frac{\rho_l u d}{\mu_l}$
t	time, s
T	temperature, °C
u	velocity, m/s
U	overall heat transfer coefficient, W/m^2-K
v	heat-exchange region velocity, m/s
W	gross turbine output, W
x	axial location, –
y	steam fraction for deaeration, –

Greek

ε	porosity, –
$\varepsilon_{\mathrm{tank}}$	storage effectiveness, –
η	efficiency, –
μ	viscosity, kg/m-s
ρ	density, kg/m^3
Θ	non-dimensional temperature, –

Subscript

0	rated condition
c	cold
eff	effective
h	hot
heel	liquid heel
HX	power block heat exchangers
in	inlet
init	initial
l	molten salt
p	pump
rec	receiver
s	solid filler
t	turbine
w	wall
wat	steam
x	axial location

production is subsequently desired under no-sunlight conditions, salt is extracted from this tank and sent to the plant power block for steam generation. While this system is simple and effective, mass balance in the collection loop requires a second tank upstream of the solar receiver to store the excess cold salt exiting the power block. This cold tank adds to the plant cost without providing any energy benefits.

The two-tank concept can be modified to save cost by storing the excess hot and cold molten salt inside a single tank volume, removing the physical redundancy of a second tank. Separation of the hot and cold fluid is retained in this thermocline tank via fluid buoyancy forces that help stratify the two isothermal regions along the vertical direction. At the interface of the hot and cold fluid, an intermediate layer of high temperature gradient develops, known as the thermocline or heat-exchange region. This sigmoid-shaped stratification is sustained over repeated storage cycles that involve flow reversal of the internal molten salt. During operation, the tank is energized or charged with hot salt entering at the top of the tank while cold salt is pumped out of the bottom. The heat-exchange region between the hot and cold salt travels downward during this charging process until the tank reaches its energy capacity, with the contents of the entire tank reaching the incoming hot salt temperature. For the discharge cycle, the heated tank pumps out the hot salt from the top, allowing cold salt to return at the bottom via a tubing manifold. This process continues until the heat-exchange region climbs to the top of the tank and the volume of available hot salt is exhausted.

Additional cost savings are realized by filling a majority of the tank interior with inexpensive granulated rock. This porous rock bed displaces a bulk of the (more expensive) molten salt volume and mitigates fluid mixing detrimental to the thermal stratification. Material selection for this filler is not trivial; the porous bed material must exhibit long-term compatibility with repeated temperature fluctuations in the surrounding salt. Pacheco et al. [1] investigated multiple filler candidates for compatibility with molten salt and reported quartzite rock and silica sand to be optimal selections due to their low cost, chemical inertness, and physical stability under several hundred thermal cycles with hot and cold salt.

A 170 MW h_t thermocline tank was installed at the historic Solar One pilot plant in Daggett, CA [2]. The tank operated from 1982 to 1986 and was filled with Caloria HT-43 mineral oil and granite rock. The use of mineral oil as the heat transfer fluid limited the storage system to a maximum temperature of 304 °C, a temperature suitable only for auxiliary steam generation. However, the thermocline tank satisfied its original design objectives. Sandia National Laboratories later constructed a small 2.3 MW h_t tank to validate the thermocline concept with molten salt and quartzite rock filler [1]. The concept was again determined to be a valid and feasible addition to solar power plants with a projected cost savings of 33% compared to the baseline two-tank storage design.

The elevated temperature and large physical scale of the thermocline tank have limited a majority of investigations to numerical analysis. A multidimensional computational fluid dynamics (CFD) model was developed by Yang and Garimella [3] to simulate mass, momentum, and energy transport inside a molten-salt thermocline tank. A two-temperature model resolved energy transport in both the molten-salt and solid filler regions. The governing conservation equations were discretized with the finite-volume method and solved with FLUENT, a commercial CFD package. With this model, the authors investigated thermocline performance during discharge with several different tank geometries and discharge powers. Well-insulated tanks exhibited improved performance at low Reynolds numbers and increased tank heights. For non-adiabatic tanks with significant external heat losses, discharge performance instead improved with increasing Reynolds number, due to the decreased fluid residence time inside the tank and reduced exposure to the heat loss condition [4]. Xu et al. [5] later modified the adiabatic model to perform a sensitivity study of material properties on storage performance. Flueckiger et al. [6] extended the non-adiabatic model to investigate thermal ratcheting phenomena in the thermocline tank wall.