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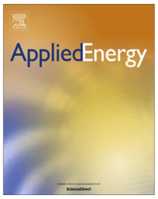

Thermo-mechanical parametric analysis of packed-bed thermocline energy storage tanks

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HIGHLIGHTS

- A numerical model of packed-bed thermocline thermal storage for CSP is presented.
- Up-to-date commercial configurations are tested both thermally and structurally.
- Promising thermal performance is obtained with a temperature difference of 100 °C.
- Reliable factors of safety against material yielding and ratcheting can be obtained.
- Cyclic relaxation-traction elastic wall stresses arise with plant normal operation.

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ABSTRACT

A packed-bed thermocline tank represents a proved cheaper thermal energy storage for concentrated solar power plants compared with the commonly-built two-tank system. However, its implementation has been stopped mainly due to the vessel's thermal ratcheting concern, which would compromise its structural integrity. In order to have a better understanding of the commercial viability of thermocline approach, regarding energetic effectiveness and structural reliability, a new numerical simulation platform has been developed. The model dynamically solves and couples all the significant components of the subsystem, being able to evaluate its thermal and mechanical response over plant normal operation. The filler material is considered as a cohesionless bulk solid with thermal expansion. For the stresses on the tank wall the general thermoelastic theory is used. First, the numerical model is validated with the Solar One thermocline case, and then a parametric analysis is carried out by settling this storage technology in two real plants with a temperature rise of 100 °C and 275 °C. The numerical results show a better storage performance together with the lowest temperature difference, but both options achieve suitable structural factors of safety with a proper design.

1. Introduction

Concentrated solar power (CSP) plants have become one of the most reliable promises for a sustainable energy future. They are able to transform the solar radiation into electricity by means of a collector system and a thermodynamic power cycle. The collector involves a set of reflectors that focuses the sunlight on a point (power tower, parabolic dish), or along a line (parabolic through, Fresnel). A heat transfer fluid (HTF) is pumped to the reflectors focal region so that it absorbs the thermal energy. In many applications, this hot fluid works as the hot source within the power cycle by evaporating water. Eventually, the resulting steam moves a turbine and the electrical generator.

As a result of the day/night cycle and the weather, a thermal energy storage (TES) is essential, which is able to match supply and demand of energy in order to be commercially viable. This system collects the surplus thermal energy and provides it when there is not enough solar radiation to cover all the demand. The current standard storage for CSP is the two-tank molten salt TES in which there is a separate tank for the hot and cold fluid. Since its associated investment and operational costs are relatively high, different cheaper approaches have been considered.

In this sense, containing both fluids in a single thermocline storage tank is becoming a promising alternative as can be observed in the literature [1–3]. The common design is a dual-media vessel containing the HTF and an inert granulate material, preferably quartzite rock and silica sand [4], which works as a porous medium. It is based on the principle of buoyancy stratification to separate hot and cold fluid; the former with a lower density at the top,

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Nomenclature

Roman letters

$\mathbf{1}$	identity tensor
A	surface area, m^2
AR	aspect ratio
A_t	transversal area of the bed, m^2
A_w	internal surface area of the tank wall, m^2
B	exergy, J
C_p	specific heat capacity, J kg^{-1} K^{-1}
D	diameter, m
DNI	direct normal irradiance, W m^{-2}
e	tank wall thickness, m
E	Young's modulus of elasticity, N m^{-2}
$\boldsymbol{f}$	body force per unit mass, N kg^{-1}
FoS	factor of safety
g	gravitational acceleration, m s^{-2}
h	height, m
K_a	active pressure constant
K_p	passive pressure constant
k	thermal conductivity, W m^{-1} K^{-1}
$\dot{m}$	mass flow, kg s^{-1}
n	number of filler particles
$\boldsymbol{n}$	unitary normal vector
p	pressure, N m^{-2}
Q	thermal energy, J
R_{conv}	convection resistance between fluid and particles, K W^{-1}
r, θ, z	tank cylindrical coordinates, m, rad, m
SM	solar multiple, m^2 m^{-2}
T	temperature, K
t	time, s
U_{TC-Sh}	fluid-shell heat transfer convection coefficient, W m^{-2} K^{-1}
$\boldsymbol{u}$	displacement vector, m
V	volume, m^3
$\boldsymbol{v}$	velocity vector, m s^{-1}
W	work, J
$\tilde{z}$	depth of the fluid column, m

Greek symbols

α	thermal expansion coefficient, K^{-1}
Δt	time interval, s
$\boldsymbol{\varepsilon}$	strain tensor, m m^{-1}
ϵ	porosity
η	efficiency
μ, λ	Lamé parameters, N m^{-2}
μ_{visc}	viscosity, kg s^{-1} m^{-1}
ν	Poisson's ratio
ρ	density, kg m^{-3}
$\boldsymbol{\sigma}$	stress tensor, N m^{-2}
σ_{eq}	von Mises stress or equivalent tensile stress, N m^{-2}
σ_y	material yield strength, N m^{-2}
ϕ	angle of internal friction, rad

Superscripts and subscripts

C	charge process
CO	cut-off
D	discharge process
f	fluid
in	inlet conditions
int	internal
out	outlet conditions
R	restart
s	filler material

Acronyms

CSP	concentrated solar power
EG	electric generator
HTF	heat transfer fluid
PB	power block
SF	solar field
TES	thermal energy storage

and the latter at the bottom. Thus, a charging process (i.e. heating) is carried out by introducing the HTF from the upper tank section and a discharging process (i.e. cooling) from the base. The main benefit of the filler material is the reduction of higher-cost fluid required, since the solid is acting as the major sensible heat storage medium. This, together with the use of one tank instead of two, is translated in costs savings of approximately 33% compared with the two-tank molten salt approach [5,6].

Despite its proven potential, there is still a critical concern that has stopped it from being implemented in commercial plants. It refers to thermal ratcheting, a phenomenon that might compromise the structural integrity of the system [7,5,8]. It may occur when a tank filled with particulate solids is cyclically heated and cooled. As long as the wall has a greater thermal expansion than the filler material, a radial gap is generated between both during heating, allowing the cohesionless particles to settle lower to fill it. When temperature drops, the tank is unable to contract completely, resulting in thermal stresses that may cause plastic deformation. If the strain hardening cannot prevent the same process in the next heating and cooling cycles, the tank wall will be slowly ratcheted outward until it fails.

Some technological solutions have already been suggested in order to elude the thermal ratcheting matter. A composite wall for the vessel has been proposed by [8]. It settles an insulation layer between the inside and the metal shell, to minimize the wall temperature variation and consequently, the potential of ratcheting. A buried concrete tank with a truncated cone shape for guiding the rocks upwards during thermal expansion and, therefore, reducing lateral pressure on the walls, has been tested and modeled [9]. Air worked as HTF and no liquid option was contemplated. Another concept removes all the solid filler material, obtaining a single-media thermocline tank with fluid only [10]. Even though convective mixing flows are significant without the porous media, the thermal diffusivity lessens, so it can achieve a slightly better thermal function. A structured packed thermocline tank can also be considered as a viable proposal [11–13]. Different arrangements of structured material can be chosen to replace the packed aggregated bed so as to avoid solid filler settlement. The principal disadvantage of all these alternatives compared with the original thermocline rests on economics.

Although there have been an extensive research regarding heat transfer and storage performance of thermocline tanks [6,14–17], few works have carried out a mechanical analysis that addresses the ratcheting issue. The design of the experimental thermocline system of Solar One Pilot Plant [18,19] imposed a high yield strength material for the tank wall in order to avoid any plastic deformation. It was developed considering the active load of the inner gravel and its differential expansion with the shell. Only a particular stress state was evaluated: the cooldown from maximum temperature to ambient temperature with an assumed rigid