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Influence of flow distribution on the thermal performance of dual-media thermocline energy storage systems

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HIGHLIGHTS

- The effects of flow distribution are studied for molten-salt thermocline TES tanks.
- Non-uniform flow slightly increases the useable energy output in the discharge.
- Non-uniform flow enhances the heat transfer and decreases the thickness of the thermocline layer.
- Interstitial heat transfer is responsible for most of the entropy generation in the discharge.
- Non-uniform flow reduces the entropy generation in the discharge.

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ABSTRACT

Dual-media molten-salt thermocline thermal energy storage (TES) systems can be used to maintain constant power production at Concentrated Solar Power (CSP) plants independent of weather changes at costs less than that of traditional two-tank molten-salt storage systems. The flow distribution is a critical parameter affecting the thermal performance but has rarely been considered for dual-media TES systems in previous studies. This study analyzes the influence of the flow distributions at the inlet and outlet of a salt-rock dual-media thermocline TES tank on the thermal performance. The flow distribution is characterized by radial component, and a two-temperature model is used to investigate the thermal performance of the thermocline tank. The model is first validated against experiment data available in the literature and then used to study the discharge process of the thermocline thermal storage tank for various flow distributions. The results show that even with a large (80% of the area) flow blockage at the inlet, the flow distribution has only a limited influence on the useable energy output (<3% change) of the dual-media storage tank. In fact, the flow non-uniformities reduce the thickness of the thermocline layer and slightly increase the useable energy output, whereas non-uniformities at the top outlet slightly decrease the output. An entropy generation analysis, including the effects from diffusion and interstitial heat transfer, is performed to further explain these phenomena. The interstitial heat transfer is found to be the main cause for the entropy generation in the discharge. Flow non-uniformities are also found to reduce the entropy generation.

1. Introduction

Molten salts are viable candidates for high-temperature (>400 °C) heat transfer fluids (HTFs) in Concentrated Solar Power (CSP) plants due to their low costs and operating pressures relative to currently used high-temperature oils. Molten salts have stable heat transfer properties, and their heat transfer characteristics can be well predicted by experimentally verified correlations [1–3]. One major disadvantage of molten salts is their relatively high solidification temperatures, which cause difficulties when using the salts in heat transfer loops. As a hot molten salt flows into a cold tube, the salt first cools in the region closest to the tube wall, then solidifies and is later re-melted by fresh hot salt [4]. The air-salt interface first increases quickly, then fluctuates and finally stabilizes [5]. The salt solidification greatly increases the flow pressure loss and increases the filling time [6]. Preheating of the tubes may be necessary to eliminate the risk of tube blockage when filling the tubes with molten salts.

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Nomenclature

A_f	flow area at the tank boundary
c_p	specific heat (J/kg-K)
d	thermocline tank diameter (m)
d_s	filler particle diameter (m)
F	inertial coefficient, $F = \frac{1.75}{\sqrt{150\varepsilon^3}}$
g	gravity (m/s^2)
h	thermocline tank height (m)
h_i	interstitial heat transfer coefficient (W/m^3 K)
Δh	thermocline thickness (m)
K	permeability, $K = \frac{d_s^2 \varepsilon^3}{175(1-\varepsilon)^2}$ (m^2)
k	thermal conductivity (W/m-K)
P_{TES}	electrical power of concentrated solar power plant (W)
Q_v	volumetric flow rate of the molten-salt (m^3/s)
p	pressure (Pa)
S	entropy (J/K)
T	temperature (K)
T_0	temperature of reference environment (K)
t	time (s)
$\mathbf{u}$	molten salt velocity vector (m/s)
X_{dest}	exergy loss (J)
x	tank axial coordinate (m)
y	tank radial coordinate (m)

Greek

ε	porosity (–)
η	efficiency (–)
η_p	thermal to electricity conversion efficiency
μ	molten salt viscosity (Pa-s)
v	molten salt kinematic viscosity (m^2/s)
Θ	non-dimensional temperature, $\Theta = \frac{T - T_C}{T_H - T_C}$ (–)
ρ	density (kg/m^3)

Non-dimensional variables

Re	Reynolds number $Re = \frac{\lvert\mathbf{u}\rvert d_s}{v}$
Nu_i	Interstitial Nusselt number $Nu_i = \frac{h_i d_s^2}{k_l}$
Ec	Eckert number $Ec = \frac{\lvert\mathbf{u}\rvert^2}{c_{p,l}(T_H - T_C)}$
Pr	Prandtl number $Pr = \frac{\mu c_{p,l}}{k_l}$
Da	Darcy number $Da = \frac{K}{h^2}$

Subscripts

C	cold end of the tank
H	hot end of the tank
l	molten salt phase
s	solid filler phase
i	interstitial
gen	(entropy) generation
e, eff	effective

Molten-salt thermal energy storage (TES) systems have been widely used in Concentrated Solar Power (CSP) plants [7] to produce electricity independent of the weather conditions. Of the various TES technologies, the dual-media molten-salt thermocline TES has been recognized as a promising approach due to its relatively high energy efficiency and low cost [8]. A dual-media molten-salt thermocline TES system is primarily a tank filled with a filler material (rock and sand) as the main storage medium with a molten-salt HTF in the pores between the filler particles.

The flow and heat transfer characteristics in molten-salt thermocline TES systems have been carefully studied to gain a better understanding of the thermal performance. Yang and Garimella [9] developed a two-temperature numerical model of a thermocline TES system with the heat transfer between the salt and the filler particles represented by an interstitial Nusselt number. They also studied the effects of the thermal conditions at the tank wall and found that a non-adiabatic wall only slightly reduced the efficiency for wall Nusselt numbers smaller than 10^4 [10]. Later, Flueckiger et al. [11] investigated the thermal and mechanical performance of a discharging thermocline tank. The mechanical stress caused by thermal ratcheting was found to be well predicted by a simplified one-dimensional model using Hook's Law. Xu et al. [12] presented a parametric study of a molten salt thermocline TES system, which showed that the mean inlet velocity had a negligible effect on the discharge efficiency and thermocline thickness with only a slight increase in the efficiency. They suggested the reason for this was a trade-off between the two counteracting effects of the increasing velocity, which increased the thermocline thickness due to the shorter heat transfer time between the solid and liquid, and the reduced time for conduction within the particles, which reduced the thermocline thickness. Yang and Garimella [13] studied the cyclic operation of molten-salt thermocline tanks and found that for a specific power cycle, an increase in the tank height increased the thermal efficiency. Recently, Flueckiger and Garimella [14] reviewed the numerical studies performed on thermocline storage systems.

All of these studies assumed uniform flow velocity in the thermocline tank with no consideration for the effects of the flow distribution. Consequently, the flow distribution effect is not clearly understood, despite being a practical concern in TES systems. For instance, the flow enters a storage tank through a distribution system with multiple manifolds, as shown in Fig. 1. The flow rates through these manifolds may differ due to different flow distances and pressure losses, resulting in non-uniform flow across the diffuser. In addition, the manifolds may leak or become blocked during operation, leading to flow rate variations across the diffuser. Flow distribution has been found to be important in water (single-medium) thermal storage systems [17–22]. A recent experimental study [23] on hot water solar energy storage validated that the inlet flow distribution could lead to a change of 40% in the effective discharge efficiency. Therefore, flow distribution may also be important in dual-media thermocline TES systems and needs to be carefully considered. Until now, few studies have been found on the influence of the flow distribution on the thermal performance of dual-media thermocline TES systems.

This study aims to investigate the influence of the flow distributions at the bottom and top of a thermocline TES tank on the thermal performance. The flow distribution is characterized by radial component with its influence analyzed in this study. A two-temperature model is used to investigate the effects of the flow distribution on the discharge process of the thermocline tank. An entropy generation analysis is performed to include the effects of the diffusion and interstitial heat transfer on the energy degradation in the tank.

2. Numerical model

2.1. Problem description

A schematic illustration of a TES thermocline tank is shown in Fig. 2. The tank is packed with quartzite rock, and a molten salt fills the pores between the rock particles. Initially, the rock and the