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Numerical modeling and analysis of dual medium thermocline thermal energy storage

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ABSTRACT

In this study, a computational model is developed to investigate packed-bed thermocline thermal energy storage. Its three-dimensional transport mechanisms are simulated under different flow conditions, and the transport model is based on a macroscopic version of the k–epsilon equation for turbulent flow conditions. Dispersive and secondary heat transfer have also been considered for turbulent flows. The thermal characteristics and efficiency of the system are examined under different operational and geometrical conditions for the charging and discharging processes for a fixed thermal energy storage size of 50 MWh.

The Taguchi method is used to optimize the design parameters of the thermocline thermal energy storage system. Its performance is evaluated by performing numerical simulations based on a three-dimensional computational fluid dynamics (CFD) model. In this study, the effects of the variations in parameters such as the inlet fluid Reynolds number, aspect ratio, porosity, and filler size, on the storage performance are also evaluated. The optimal condition and geometry of the thermocline thermal energy storage system are determined by the CFD–Taguchi combined method. The analysis results indicate that the porosity and aspect ratio are the most important design parameters for thermocline thermal energy storage.

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1. Introduction

A concentrated solar power (CSP) plant utilizing thermal energy storage (TES) is a promising, clean, and cost-competitive technology for large-scale power generation. The application of TES in a CSP plant increases the hours of electricity generation, improves the operational flexibility, and assists in reducing the levelized cost of electricity [1].

Molten salt-based TES has been identified as a potential heat storage system [2] offering a good balance of cost, capacity, and efficiency. Presently, two types of molten salt-based TES systems are available, namely, one-tank system and two-tank system. The two-tank system has been successfully established in various commercial troughs and a tower solar thermal power plant [3]. The one-tank storage system provides dual medium-based thermocline TES. A comparison of the two systems was conducted [4], showing that the cost of the thermocline one-tank storage is 35% less than that of the two-tank storage. It is reported that thermocline storage filler materials are widely available, compatible with nitrate salts, and non-hazardous and have a high heat capacity and void fraction [5]. Quartzite and silica sand was tested and found to withstand the molten salt environment and retain its thermal property for the thermal charging and discharging cycles [5]. A pilot prototype of a 2.3-MWh thermocline TES system was experimentally tested and reported [6]. The thermal behavior of a packed-bed molten salt-based thermocline TES was experimentally cross verified by a one-dimensional Schumann equation-based numerical model [6]. A thermocline TES model based on the packed bed approach applied to a one-tank system has already been developed. A comprehensive transient model was developed [7] taking into account the effects of different parameters. A parametric study of thermocline TES under a variable velocity, tank height, and porosity is reported in the literature [8].

A porous media flow occurs in a dual medium thermocline TES system. The Reynolds number (Re_p) based on the particle size is considered to determine the flow regime. Re_p in range of 150–300 corresponds to a hydrodynamic dispersive flow due to the spatial deviation [10]. The literature defines the following distinct flow regimes [11]: (a) Darcy or creeping flow regime ($Re_p < 1$), (b) Forchheimer flow regime ($1–10 < Re_p < 150$), (c) post-Forchheimer flow regime (unsteady laminar flow, $150 < Re_p < 300$), and (d) fully

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Nomenclature

A	Area tank, m^2
a_{sf}	Specific area, m^{-1}
C_p	Specific heat, J kg^{-1} K
C_μ	Empirical constant, (0.09)
D	Diameter of thermocline tank, m
d_p	Diameter of filler granules, m
epsilon_d	Turbulent dissipation
f	Inertial coefficient,
Gr	Grashof number
g	Acceleration due gravity, m/s^2
H	Height of thermocline tank, m
h_{sf}	Interstitial convection coefficient, W/m^2 K
I	Unity tensor
L_R	Turbulent kinetic energy, J kg^{-1}
m	Mass, kg
m	Mass flow rate, kg/s
Nu	Nusselt number
P	Pressure, Pa
Pr	Prandtl number
Pe_d	Peclet number
R	Permeability, m^2
Re_p	Reynolds number
Str	Stratification number
SNR	Signal-to-noise ratio
t	Time, s
T	Temperature, K
th_n	n^{th} insulation thickness, m
U	Wall heat transfer coefficient, W/m^2 K
$\overline{U}$	Velocity vector, m/s
V	Volume, m^3
Y	Axial distance, m
ε	Porosity
λ	Thermal conductivity, W/m K
η	Efficiency
μ	Viscosity, Pa s
ρ	Density, kg/m^3
τ	Reynolds stress tensor
β	Expansion coefficient

Subscript

Amb	Ambient
Avg	Average
C	Charging
D	Discharging
Disp	Dispersion
disp,t	Turbulent dispersion
Diff	Diffusive
eff	Effective
e	Equivalent
f	Heat transfer fluid
Inn	n^{th} layer of insulation
Ini	Initial
Inlet	Inlet
ref	Reference
s	Solid filler
S	Storing
sf	Interfacial
T	Turbulent
Tor	Tortuosity
W	Wall
′	Fluctuating component
–	Average component

turbulent flow regime ($Re_p > 300$). Various modeling efforts are reported in the literature for a turbulent flow [11]. In this study, Reynolds-averaged Navier–Stokes (RANS) equations are solved for a unidirectional flow in a porous medium. The macroscopic flow transport equation for a turbulent flow in a porous medium is based on the time- and volume-average mathematical model developed by Pedras [12]. To consider the turbulence in the porous structure, an additional term involving k and epsilon is required.

Numerous studies on thermocline TES systems are reported, including evaluation of their thermal behavior and efficiency. A one-dimensional simplified model has also been presented to determine the thermocline TES characteristics [5]. The following are the various technical gaps limiting the large-scale applications of dual-media thermocline TES [7–9]: (1) a three-dimensional (3D) study considering the thermal non-equilibrium heat transfer between the fluid and solid particles has not been conducted, (2) the behavior of a thermocline bed at various flow rates has not been examined, (3) the effect of flow in the interstitial heat transfer between the molten salt and solid fillers and the effective thermal conductivities of the molten salt and solid fillers have not been evaluated, and (4) a study of the optimal design parameters has not been performed.

The aim of this study is to develop a transient 3D model to predict the thermal characteristics of packed bed molten salt-based thermocline TES under laminar and turbulent flow conditions. The developed model is validated with the experimental results reported in the literature. The analysis results present various aspects of the thermocline TES system including the thermal characteristics, temperature distribution, stratification behavior, and efficiency.

The effects of some key design parameters such as the inlet flow, temperature, porosity, filler diameter, and aspect ratio on the thermal performance of the thermocline TES are presented. The Taguchi method is used for obtaining the optimal combination of these parameters. This work can provide a guideline for selecting the TES system design configurations and operational strategies for achieving an enhanced system efficiency.

2. Modeling of thermocline storage

2.1. Governing equation

Fig. 1. shows a schematic of the thermocline TES system. A porous media flow and heat transfer model are considered. The equations are formulated as to present a set of conservation laws, whereas the constitutive equations are specific to the stationary packed beds of spherical particles. A typical thermocline pebble bed consists of an annular vessel filled with equal-sized pebbles, as shown in Fig. 2. The pebbles (solid filler) are randomly packed, and the heat transfer fluid (HTF) circulates through the interstitial voids between the pebbles.

A transient 3D model is used to represent the transport phenomena in packed-bed thermocline TES. A generalized or continuum model based on the method of volume-averaging is adopted. This approach attempts to obtain a solution with sufficient accuracy. The method employs the governing equations expressed in terms of the intrinsic volume-averaged quantities, and the constitutive relations in the governing equations account for the pore-scale phenomena. The following assumptions are made:

- The viscous dissipation effects and the kinetic energy contribution to the fluid-phase total energy are assumed to be negligible for a laminar flow.
- The heat transfer properties of the fluid material are assumed to be independent of the variation in the pressure field.

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