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INTRODUCTION

Dynamic Energy Transport and Integration Lab (DETAIL) at Idaho National Laboratory is to support experimental demonstration and validation research on Nuclear-Renewable Hybrid Energy System [1]. The Thermal Energy Distribution System (TEDS) is a thermal-hydraulic flow loop in DETAIL with its own dedicated control system to support the integration of co-located multiple experimental systems, where a packed-bed thermal energy storage (TES) is installed as a thermal buffer and storage unit. Among various TES options, the packed-bed TES is adopted in TEDS because it offers a low-cost single-tank thermal storage option compared to the traditional two-tank TES. However, since the TES tank is filled with granular fillers having different thermophysical properties from those of TES tank wall, there is a potential thermo-mechanical issue to be carefully addressed like thermal ratcheting which may pose a significant design concern for the packed-bed TES tank. Thermal ratcheting is a thermomechanical process caused by the repeated rearrangement of granular filler inside a TES tank during continuous thermal cycling operation of the packed-bed TES system. If the thermally induced stress exceeds the yield strength of a TES tank wall, catastrophic consequences may happen like rupture of the TES tank. Thus, it is important to understand the phenomenon to ensure the robust operation of the packed-bed TES tank. Given that thermal ratcheting is caused by complex interaction of thermal transport in the porous bed and solid mechanics, the accurate prediction of transient thermal behavior of the packed-bed TES tank, which is the focus of this paper, is critical to the reliable thermal ratcheting analysis.

This paper discusses the numerical modeling, simulation, and validation studies that are ongoing at INL to investigate the transient thermal behavior of the packed-bed TES. Of particular concern is the transient thermal process occurring in the packed-bed TES unit that is operated in conjunction with the INL TEDS. The main goal of this research is three-fold: (i) provide preliminary insights into the transient thermal behavior of the TEDS TES tank, (ii) support the thermal measurement and validation plan for TEDS experiment, and (iii) provide transient thermal boundary conditions to support the reliable thermal ratcheting analysis of the TEDS TES tank. For the transient thermal modeling and analysis, a CFD model was developed, and the validity of the modeling approach was examined via comparing the numerical simulation results with the experimental data obtained from various design characteristics of packed-bed TES tanks. Then, the present modeling method was applied for the transient thermal analysis of the TEDS TES tank, and the results are discussed along with the potential improvement of data acquisition strategy for the future TEDS experiments for more precise validation study.

EXPERIMENTAL DATABASE

The present study is performed by comparing the transient numerical simulations of packed-bed TES tank during the cyclic operations of charge and discharge modes with experimental data. For the validation of thermal model, the thermal measurement data obtained by Esence et al. [4], Pacheco et al. [5], and INL (TEDS experiment) [6], from the various design characteristics and scales of packed-bed thermocline TES tanks, were utilized. Note that the present modeling effort is closely related to the INL's stress modeling and validation research for TEDS TES which requires the thermal analysis results as modeling boundary conditions [7].

In Table 1, the design characteristics of the packed-bed TES tanks used to validate the present thermal modeling approach is summarized. In the TEDS experiment, multiple thermocouples as well as strain gages were installed in the TES tank to detect axial and radial temperature distribution, tank wall temperature, and thermal strain. And recently, some experimental data were obtained during the startup and commissioning testing of the TEDS [6].

CFD MODEL FOR TRANSIENT THERMAL ANALYSIS OF PACKED-BED TES

Model Description and Relevant Assumptions

This study employed a two-dimensional (2-D) porous media modeling approach to simulate the transient thermal behavior of packed-bed TES tank. Of particular concern is the transient thermal behavior during the cyclic operation of charge and discharge processes. The STARCCM+ (version 15.06), a commercial CFD tool, was used to develop the present thermal model . A transient laminar flow solver was employed by considering the Reynolds number, characteristic length scale of the porous bed, and fluid's thermal properties for the test problems used in this study.

Fig. 1 shows an example of meshing strategy applied to the present CFD simulations of the packed-bed TES tanks during this study. The domain was discretized with quadrilateral type mesh. The TES tank wall was also modeled to account for the wall influence on the thermal response of the porous bed during the charge and discharge processes. The prism layer type mesh was applied at the near-wall region to better capture the velocity profile close to the wall.

TABLE I. Design Characteristics of Packed-bed TES Tanks for the CFD Model Validation

	Esence et al. [4]	**Pacheco et al. [5]**	**INL TEDS [6]**
Storage Capacity	-	2.3 MWh_{th}	200 kWh_{th}
Tank shape (D_{in} / h_b)	Cylindrical (1.0m/3.0m)	Cylindrical (3.0m/5.2m)	Cylindrical (0.88m/3.55 m)
Tank wall material	Stainless steel	Carbon steel	Carbon steel
Filler material	Silica gravel and silica sand	Quartzite rock and silica filter sand	Alumina bead
Bed porosity	0.27	0.22	0.4
Heat transfer fluid	Therminol® 66	Nitrate Salt	Therminol® 66
Operation temperature	85-150 °C	290-396 °C	225-325 °C

To address the heat transfer within a porous bed, the porous media thermal non-equilibrium model in STARCCM+ was employed, where the fluid and porous phase each have their own temperature, rather than being treated as a homogeneous mixture. This model considers the heat transfer based on the temperature difference between the working fluid and the porous phase. The heat transfer coefficient and interaction surface area to determine the heat transfer between the two media were obtained using the correlation employed by Lew et al [8] and originally provided by Nelis and Klein [9]. The heat transfer coefficient to estimate the heat loss through the TES tank wall was determined as suggested by Esence et al (2019) [4].

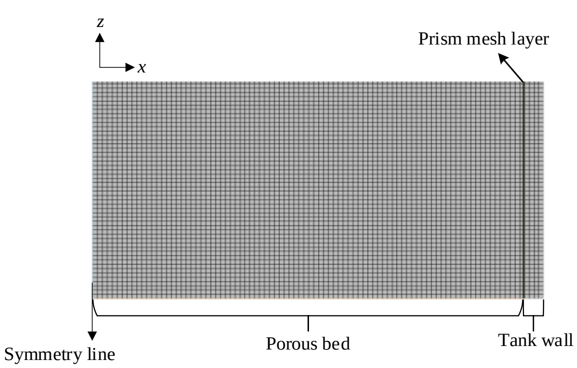

Fig. 1. 2-D mesh configuration for the present CFD simulation of packed-bed TES tank.

For the present transient simulation, a time step size of 1.0 sec was employed. The numerical solution at each time step was considered converged when the scaled residuals of the mass, momentum, and energy equation were reduced to 10^{-4}, 10^{-4}, and 10^{-6}, respectively.

The initial and boundary conditions of all the CFD simulation cases were determined based on the experimental measurements (e.g., initial temperature distribution, transient inlet fluid velocity). Also, the temperature-dependent material properties were considered as user defined functions in order to correctly model the transient thermal response of the porous medium during the charging and discharging processes of the packed-bed TES tank.

The relevant modeling assumptions applied to the present CFD analysis, i.e., thermal model, can be summarized as follows:

(i) The fluid flow through the porous bed is incompressible.

(ii) Temperature-dependent properties of the fluid, filler particles, and tank wall are considered.

(iii) Porosity is constant across the porous bed.

(iv) The heat conduction inside the filler particles is neglected (Bi <0.1). Note, however, that the thermal diffusion across the porous bed and the heat transfer between the fluid and filler particles are addressed using the effective thermal conductivity and heat transfer coefficient, respectively.

(v) The effect of radiation heat transfer is neglected due to the relatively low operating temperature of the packed-bed thermocline tanks subjected to the current study.

RESULTS AND DISCUSSION

To validate the present CFD (thermal) modeling approach, the model prediction results were compared with the experimental data obtained by Esence et al. [4] and Pacheco et al. [5]. It is noted that the experiment performed by Esence et al. [4] used the same working fluid as TEDS (Therminol® 66) with the packed-bed thermocline tank of similar dimensions (operating temperature range: 90 - 150 ℃), while the experiment by Pacheco et al. [5] was performed with much larger scale of TES tank using molten salt as the working fluid (operating temperature range: 290 - 400 ℃). For more detailed information of these experiments, readers are advised to refer to the Refs. [4, 5].

The comparison between the present CFD model predictions and the experimental data acquired from the two different characteristics of packed-bed TES experiments is shown in Fig. 2 and Fig. 3. The comparisons present that the thermal front evolution during the charging and discharging processes of the packed-bed TES tanks are predicted quite well by the current modeling approach, regardless of the inlet boundary conditions (e.g., inlet fluid velocity) and tank scales tested in this study.

Using the modeling strategy that yielded the validation results presented in Fig. 2 and Fig. 3, a CFD model was developed for the TEDS TES tank. Although the current data obtained from TEDS are somewhat preliminary in terms of limited TES operation scenario and data sampling procedure, the comparative study between CFD simulation and TEDS data was performed in an effort to identify the potential improvements in the future experiment for more precise validation research and to verify the performance of the computational models developed in this study.

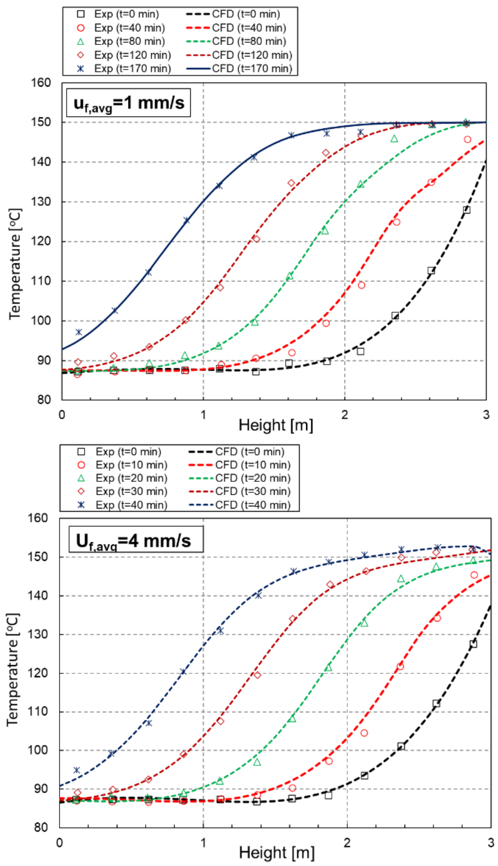

Fig. 2. Fluid temperature evolution within a packed-bed TES tank during a charge mode, compared against experimental measurement by Esence et al. (2019) [4].

In Fig. 4, the CFD predictions for the transient evolution of the temperature profile along the TES tank is compared with the experimental data during the charge (top) and discharge (bottom) operation modes of the TEDS TES tank. It is noted that due to the highly fluctuating characteristics of the raw data, the exact inlet boundary conditions of the experiment, such as transient inlet mass flow rate, could not be applied to the CFD model. This results in the greater discrepancy between the CFD predictions and the experimental data as shown in Fig. 4, relative to the comparison shown in Fig. 2 and Fig. 3. That is, the discrepancy between the CFD prediction and the TEDS experimental data shown in Fig. 4 is mainly likely attributable to the substantial uncertainty of the boundary conditions, including the inlet mass flow rate, inlet fluid temperature, and wall thermal loss rate.

During the validation studies shown in Fig. 2 and Fig. 3, it was learned that the current model prediction results were substantially sensitive to the boundary conditions such as transient inlet flow rate and transient inlet fluid temperature. Thus, it is very important to apply the well-defined (transient) boundary conditions measured from experiments in order to precisely predict the thermal field propagation across the porous bed and tank wall from the present modeling approach.

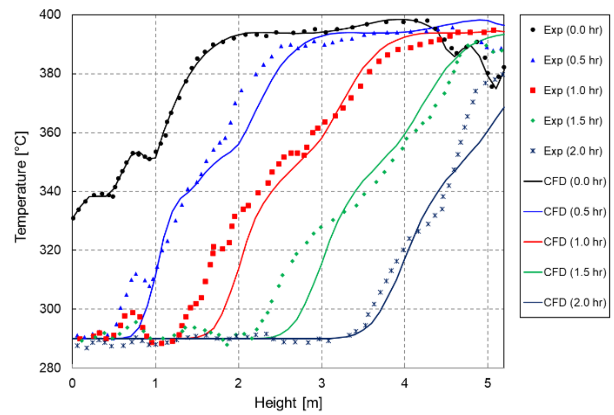

Fig. 3. Fluid temperature evolution within a packed-bed TES tank during a discharge mode, compared against experimental measurement by Pacheco et al. (2002) [5].

During the data analysis for the comparative study between CFD model predictions and TEDS data, several items to be addressed for the future TEDS experiment were observed:
(i) An optimal data sampling strategy seems to be needed to better capture the physical processes occurring in TEDS. Currently, data is collected at a rate of once per second, which can lead to substantial fluctuations with noise signal (e.g., inlet mass flow rate), making it difficult to define representative boundary conditions for precise validation.
(ii) An inconsistency was noticed for some thermal measurements. For example, the thermal sensors installed at the centerline of the TES tank tend to detect lower temperature compared to those close to the tank wall. This may be due to the channeling that leads the hot fluid from the top of the thermocline tank to flow towards the walls of a porous bed. However, the temperature difference existed even before the fluid started flowing through the tank, indicating that there might be an issue, such as calibration, with the thermal sensors installed at the centerline.
(iii) The measurement uncertainties for the relevant physical parameters, such as transient inlet mass flow rate and inlet temperature into the TES tank, need to be better defined (quantitatively), requiring additional repeatability tests.

These improvements for future TEDS experiments will allow more precise validation of the computational models when data become available from the various operating modes of TEDS.

SUMMARY AND FUTURE WORK

This paper discusses the transient thermal modeling and validation research for analyzing transient thermal behavior of the packed-bed TES during its cyclic operation of charge and discharge processes. A CFD model was developed, and validation was performed with the experimental data obtained from various design characteristics and scales of packed-bed TES tanks. The CFD model predictions generally showed good agreement with the experimental measurements. However, the model predictions showed somewhat larger discrepancy with the data obtained during the preliminary test of the TEDS TES tank. The main cause of this is likely due to the substantial uncertainty of the boundary conditions given from the experiment. Based on the comparative analysis between the present model predictions and the TEDS TES data, several potential improvements for the future TEDS experiments were suggested for more precise validation study in the future.

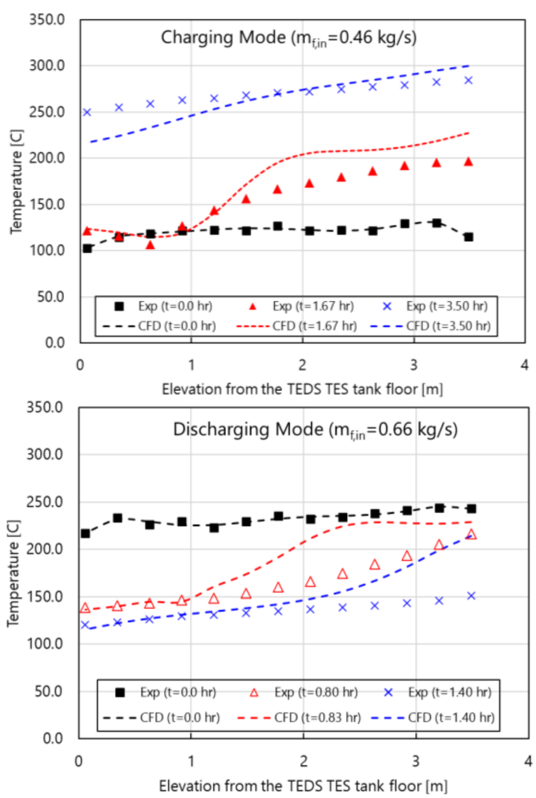

Fig. 4. Comparison of fluid temperature evolution between CFD simulation and experimental measurement during the charge mode of TEDS TES tank.

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REFERENCES

1. S. M. BRAGG-SITTON et al., "Integrated Energy Systems: 2020 Roadmap," INL EXT-20-57708 (2020).
2. M. D. A. CO. and C. U. HUNTINGTON BEACH, "10 MWe Solar Thermal Central Receiver Pilot Plant Mode 5 Charging Only Acceptance Test Procedure 1150," SAND84-8183 (1984).
3. C. M. STOOTS, A. DUENAS, P. SABHARWALL, J. E. O'BRIEN, J. YOO, and S. M. BRAGG-SITTON, "Thermal Energy Delivery System Design Basis Report," INL/EXT-18-51351 (2018)
4. T. ESENCE, A. BRUCH, J.-F. FOURMIGUE, and B. STUTZ, "A Versatile One-Dimensional Numerical Model for Packed-bed Heat Storage Systems," *Renewable Energy*, vol. 133, pp. 190-204 (2019).
5. J. E. PACHECO, S. K. SHOWALTER, and W. J. KOLB, "Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants," (in English), J Sol Energ-T Asme, vol. 124, no. 2, pp. 153-159, May 2002, doi: 10.1115/1.1464123.
6. T. J. MORTON, "Thermal Energy Distribution System (TEDS) Startup and Commissioning," INL/EXT-21-64160 (2021).
7. S. Qin, J. Yoo, and T.J. Morton, "Thermal Stress Modeling and Analysis of Packed-bed Thermocline Energy Storage Tank for INL Thermal Energy Distribution System (TEDS)", in *2022 ANS Winter Meeting and Technology Expo*. 2022: Phoenix, AZ
8. J. T. Van Lew, P. Li, C. L. Chan, W. Karaki, and J. Stephens, "Analysis of heat storage and delivery of a thermocline tank having solid filler material," Journal of solar energy engineering, vol. 133, no. 2, p. 021003, 2011.
9. G. Nellis and S. Klein, Heat transfer. Cambridge university press, 2008.