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INTRODUCTION

The Thermal Energy Distribution System (TEDS) is a thermal-hydraulic flow loop at Idaho National Laboratory (INL) to support the experimental demonstration research of Integrated Energy System (IES). TEDS enables 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. The packed-bed TES is adopted in TEDS because of its benefit as a low-cost single-tank storage option compared to the traditional two-tank storage. However, thermal ratcheting is one potential design concern which is caused by the rearrangement of granular filler inside a packed-bed tank during continuous and repeating thermal cycling operation of the TES tank. If the thermally induced stress exceeds yield strength of the tank wall, it may cause catastrophic consequences like rupture of the thermal storage tank. Thus, it is crucial to understand the phenomenon to ensure the robust operation.

Based on the temperature boundary conditions given by transient thermal analyses with computational fluid dynamics (CFD) simulations [1], the thermal ratcheting analysis is conducted to evaluate the hoop stress and resultant thermal ratcheting potential of the packed-bed TES tanks. Two different modeling approaches are tested to investigate the thermal ratcheting potential: (1) infinite rigidity model and (2) Drucker-Prager (DP) model. The 'model (1)' is a conservative method assuming infinite rigidity of the granular filler inside a TES tank, whereas the 'model (2)' is a method that takes into account more realistic processes such as thermal expansion of filler and tank wall as well as inter-particle interactions during the cyclic operation of a packed-bed TES tank. The validity of each modeling method was examined by comparing the numerical simulation with the experimental data obtained from the packed-bed TES tank for Solar One Plant [2] and evaluate the thermal ratcheting potential of the TEDS TES tank [3].

EXPERIMENTAL FACILITIES DESCRIPTION

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 validating the stress analysis model for the thermal ratcheting analysis, experimental data from the packed-bed TES tank that was operated in conjunction with Solar One pilot plant [2, 4] were used. The thermal stress data from TEDS, however, were observed insignificant during the initial (preliminary) test, so were not used in this study. Fig. 1 illustrates the TES tank geometry and the associated modeling regions for Solar One Plant [5] and INL TEDS facility [6].

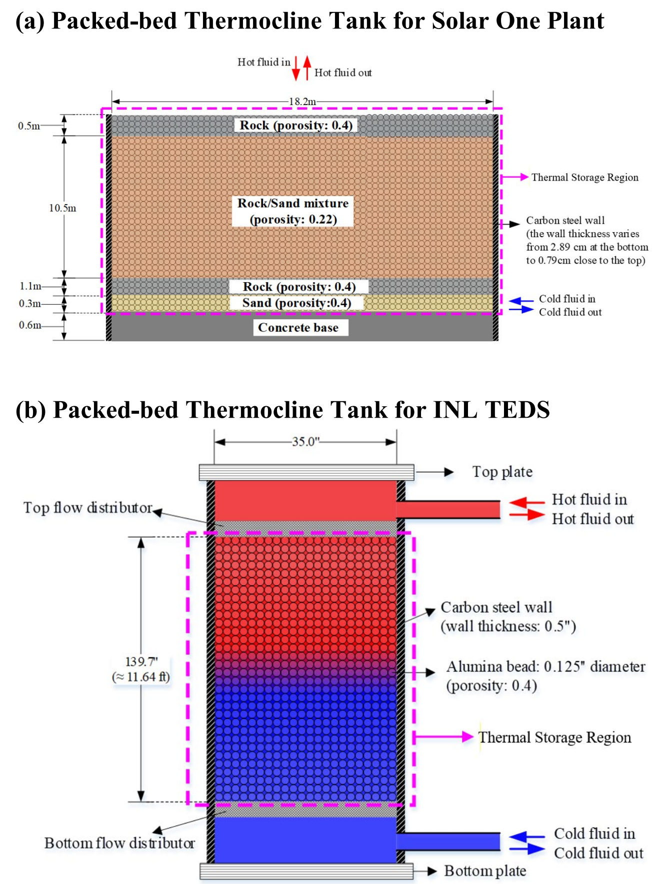

Fig. 1. Design characteristics and associated modeling geometries of packed-bed thermocline tanks for (a) Solar One pilot plant and (b) INL TEDS. Adopt from [7].

MODEL SETUP FOR THERMAL RATCHETING ANALYSIS

Given the thermal data acquired from the thermal analysis and experiment, the stress analysis was performed to investigate the thermal ratcheting potential of the packed-bed thermocline tank using the commercial software Abaqus 2018.HF3 [8]. This section describes two different modeling approaches, (i) infinite rigidity model and (ii) Drucker-Prager model, employed in this study for the thermal stress analysis during the cyclic operation of the packed-bed thermocline tank for Solar One Plant as well as INL TEDS facility.

Infinite Rigidity Model

Infinite rigidity assumption is a simplified modeling approach that assumes the filler material inside a TES tank is infinitely rigid. This approach is implemented by fixing the inner tank wall in the radial direction to prevent the tank from contracting during the simulation of discharge cycle while allowing the tank to expand freely with the temperature increase during the charge cycle. Abaqus/Standard module, which is a general-purpose Finite-Element (FE) analyzer that employs implicit integration scheme, is used with the infinite rigidity model setup. Given the fact that the infinite rigid model only requires the tank geometry without filler material inside, the material properties and stress-strain data for the TES tank wall are considered (detailed material properties can be referred to Ref.[7]).

Drucker-Prager (DP) Model

Drucker-Prager (DP) model was proposed by Drucker and Prager [9] in 1952. This model can be used to represent frictional interactions between granular solid particles in a continuum through shear-normal stress relation. This is an efficient way to mimic interaction among granular fillers in packed-bed TES tank more realistically under thermal cycling conditions while avoiding full simulation of inter-granular process. Abaqus/Explicit module, which employs explicit integration scheme to solve highly nonlinear systems with many complex contacts under transient loads, is utilized together with the DP modeling approach to take into account the interactions between the filler and tank during the thermal ratcheting process. All the parameters implemented for the DP modeling scheme used in the Abaqus simulations can also be found in Ref.[7].

RESULTS AND DISCUSSION

Investigations have been conducted on various model parameters used for the infinite rigidity and Drucker-Prager (DP) models. In this section, the simulation results of the thermal stresses and comparison with the experimental data obtained from Solar One thermocline tank are summarized. The insights into the effect of different modeling parameters for the infinite rigidity and DP models can be also useful to support the experimental setup and later test plan for TEDS TES.

Parametric Investigations and Validation

According to the literature review, there is a clear knowledge gap for the thermomechanical analysis of packed-bed thermal energy storage tank, especially with respect to DP model. There are multiple parameters determining the tank and filler material properties that need to be investigated, and the parametric study of those modeling parameters will help understand their effects during the tank's thermal ratcheting process. Given the temperature boundary conditions from the thermal analysis, we conducted the parametric study for the modeling parameters used in the stress models with the tank geometries of Solar One Plant as well as the TEDS facility. To outline the parametric study, Table I has summarized the parameters of interest for the current coupled temperature-structural analysis, including the tank material property, filler material properties, and the interaction parameters between the tank wall and the filler materials inside.

Table I. Parametric study for Solar One plant (case no. starts with "S") and the TES tank of TEDS facility (case no. starts with "T").

Case No.	Model Setup		Tank Material Property		Tank-Filler Interaction		Filler Material Property			
	Infinite Rigidity	DP Model	Thermal expansion coefficient		Wall-Filler friction coefficient		Internal angle of friction (deg)		Shear modulus (MPa)	
			1.3	1.48	0	0.5	34	60	25	75
S1	✓		✓		N/A		N/A		N/A	
T1	✓		✓		N/A		N/A		N/A	
T2	✓			✓	N/A		N/A		N/A	
T3		✓	✓			✓	✓			✓
T4		✓		✓		✓	✓			✓
T5		✓		✓	✓		✓			✓
T6		✓		✓	✓			✓		✓
T7		✓		✓	✓		✓		✓	

Infinite Rigidity Assumption

Fig. 2 presents the hoop stress profile on the Solar One TES tank wall along the axial height, evaluated with the infinite rigidity assumption. The simulated hoop stress distributions are then compared with the experimental data from Faas et al. [5] as well as the FEM analyses conducted by Flueckiger et al. [10] The simulation results show some differences at the bottom and top of the tank, The Abaqus results predicts a slower increasing trend compared to the results presented in Fluckiger et al., and this could result from the uncertainties of the TES tank constraint settings given from the experiment.

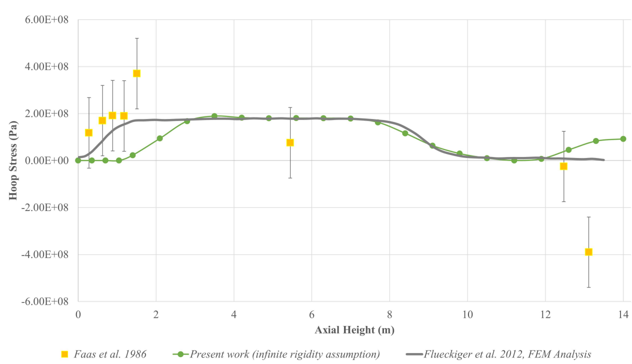

Fig. 2. Simulated hoop stresses with the infinite rigidity assumption using Abaqus and compared with the experimental data from Faas et al. [5] as well as FEM simulation results from Flueckiger et al. [10].

Similar to the investigation with Solar One TES tank, the infinite rigidity assumption is also applied to the TEDS TES tank geometry for the Case # T1 vs T2. The axial hoop stress profiles at the outer surface of the TEDS tank are plotted in Fig. 3 with two thermal expansion coefficient (TEC) settings for the tank wall material. With the infinite rigidity model assumption, the hoop stress σ at the end of the discharge cycle can be expressed as $\sigma = \alpha \cdot E \cdot \Delta T$, where α is the TEC of tank material, E the tank material's Young's modulus, and ΔT operating temperature differential along the points of interest. Therefore, a larger TEC for Case T2 results in higher hoop stress profile along the tank axial height.

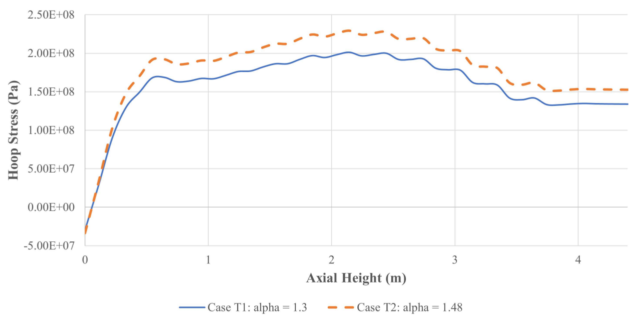

Fig. 3. Simulated hoop stresses with different TEC settings (for infinite rigidity assumption) in TEDS Case # T1 vs T2.

DP model: TEC of Tank Material

Because DP modeling scheme uses looser constraints on the tank wall nodes during the discharge period, the hoop stress profiles presented in Fig. 4 show a significantly lower magnitude compared to the stresses evaluated with infinite rigidity assumption. But, still as expected, Case # T4 with a higher TEC for the tank material still results in higher stress values than the results of Case # T3. Besides the high stresses at the tank bottom and top (because these locations endure the largest temperature changes for thermal analysis results during the heating and then cooling cycle), we can also notice that the region of a high hoop stress is observed at tank heights between 0.67 and 1.34m. This corresponds to the bottom flow distributor location shown in Fig. 1 where the filler materials are expected to re-distribute due to gravity effect by the end of the charge cycle, therefore, the hoop stresses are induced by the resisting force from the beds to the tank wall.

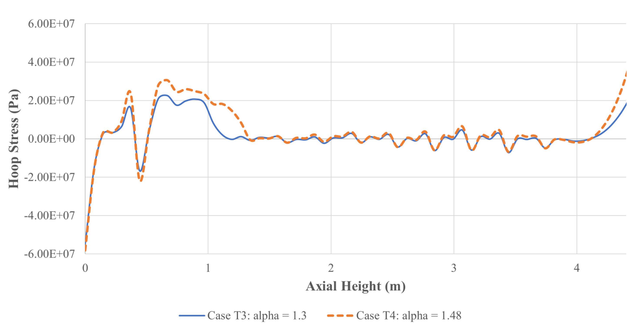

Fig. 4. Simulated hoop stresses with different TEC settings (for DP modeling) in TEDS Case # T3 vs T4.

DP Model: Wall-Filler Friction Coefficient

As shown in Fig. 5, Case T4 with a larger wall-filler friction coefficient results in a larger peak magnitude at the bottom flow distribution region, but the hoop stress decades quicker. A larger value of the wall-filler friction coefficient is expected to lead to the resistance of filler rearrangements during the discharge cycle, therefore, inducing higher hoop stress values. However, the filler beds which re-distribute due to gravity during the heating process will tend to remain staying there with the setting of a larger friction coefficient and exert forces to the tank wall during the discharge period.

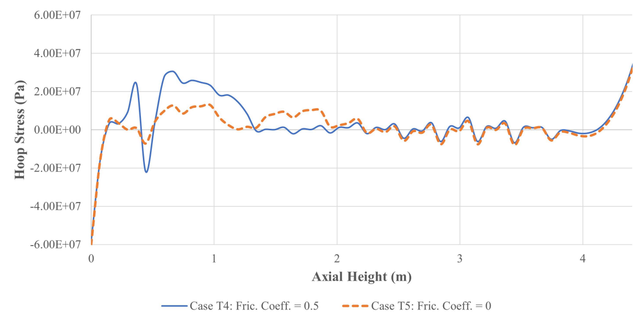

Fig. 5. Simulated hoop stresses with different wall-filler friction coefficients in TEDS Case # T4 vs T5.

DP Model: Internal Angle of Friction for Filler Material

As pointed out by Cho et al. [11], the filler behavior in the packed-bed TES depends on the initial packing states. It indicates that a higher friction angle could yield higher or lower hoop stress value highly depending on the filler materials' initial arrangement. If the filler beds are initially packed flat in the tank, there will be more filler beds to slide down and fill the gap during the charging process when increasing the friction angle. Then, this will result in a larger hoop stress on the tank wall during the following discharge cycle. The hoop stresses presented in Fig. 6 show greater hoop stress values for the case with a larger angle of friction. This implied that the filler materials were indeed packed evenly at the very beginning of the model setup.

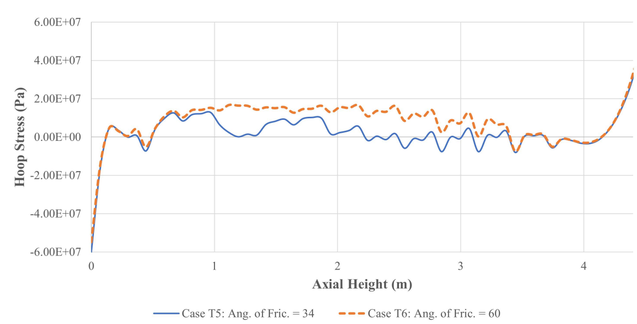

Fig. 6. Simulated hoop stresses with different internal angle of friction of filler material in TEDS Case # T5 vs T6.

DP Model: Shear Modulus of Filler Material

Shear modulus should be specified in the DP model to represent the filler bed motion inside the TES tank during the charge and discharge cycles. Defined as the ratio of shear stress to shear strain, a smaller shear modulus value indicates a solid is softer or more flexible. Filler bed inside the TES tank will experience two steps involving shear mechanism during the whole process: the first one is the re-distribution step axially due to gravity during the charge cycle, and the other is the contraction step during the discharge cycle. The resultant hoop stress profile at the end of the discharge cycle is a combined reflection from the two above steps. As shown in Fig. 7, the selected cases with two different shear moduli have a quite similar trend and magnitude of the hoop stresses except for the region (from 0.67 to 1.34m in the tank axial direction) near the bottom flow distributor of the TEDS tank. Due to the limited literature database available for the shear modulus of the materials used for TES filler beds and the complex physics of pebble re-distribution, this could be a quite interesting research topic to investigate and refine the DP modeling as future work.

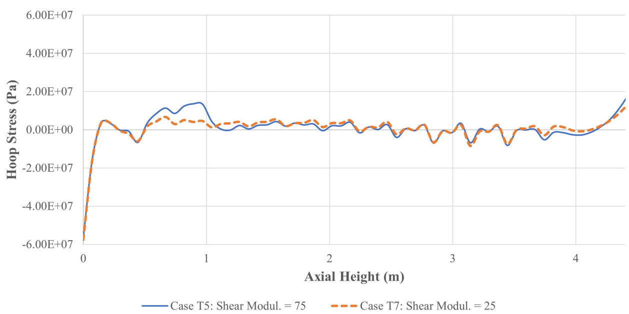

Fig. 7. Simulated hoop stresses with different shear modulus of filler material in TEDS Case # T5 vs T7.

SUMMARY AND THE FUTURE PLAN

This paper discussed the numerical modeling methods for thermal ratcheting analysis of packed-bed thermocline tank. Abaqus was utilized to perform the coupled temperature-structural analysis for the TES tanks of Solar One Plant and INL TEDS facility with two different modeling schemes: infinite rigidity model which strictly fixed the tank inner side during the discharge cycle; and DP model that simulated a more realistic filler bed behavior and its interaction with the tank wall.

Infinite rigidity assumption showed a good match for the maximum hoop stress magnitude compared with and the experimental database from Faas et al [5] and the simulation performed by Flueckiger et al. [10]. It was also noticed that the maximum hoop stresses were evaluated as linearly proportional to the TECs with the infinite rigidity model. As for DP model considering the filler-tank interactions, it was observed that the maximum hoop stresses had a larger increasing rate than the TECs of the tank material. Secondly, a larger wall-filler friction coefficient always resulted in a larger peak of hoop stresses at the bottom flow distribution region, but the stresses decayed more quickly. This is primarily caused by the effect of filler re-distribution during the charging period. What's more, the internal angle of friction for the filler material was found not to be a dominant parameter in the DP modeling. Finally, the effect from the shear modulus of the filler material properties will need more investigation as future work. Regarding the thermal ratcheting potential of the TEDS thermocline tank, both modeling methods predicted the hoop stress values that were significantly lower than the yield strength of the carbon steel (414 MPa [10]) used for TEDS thermocline tank wall, indicating that the TEDS TES tank will hold its structural integrity during the normal operating cycles.

ACKNOWLEDGEMENTS

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