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An Experimental and Numerical Investigation of a Thermal Energy Storage Sand Battery

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ABSTRACT: Thermal energy storage (TES) is increasingly recognized as a critical solution for addressing the reliability and intermittency of renewable energy sources. Large-scale TES systems, typically in the form of insulated storage tanks filled with materials like sand, rock, or phase change materials are already being utilized in power plants for clean energy storage. In addition to power generation, thermal storage technologies are finding applications in smaller-scale systems for domestic water and space heating in residential communities and districts. However, there is a growing need for experimental testing to better understand the performance of these thermal storage tanks, particularly with respect to the impact of tank size, filler material properties, and heat transfer fluid (HTF) characteristics on efficiency and cost. This study aims to design and construct a laboratory-scale experimental program to investigate the performance and thermal efficiency of a TES system using solid fillers, tailored for domestic hot water applications. The experimental setup will vary the density of the filler and the HTF type to gather essential data for calibrating existing numerical models that predict heat transfer mechanisms and system efficiency. In addition to the experimental work, a numerical analysis will be conducted to simulate the thermal response of the experimental setup. This will allow for comparison between experimental results and modeled predictions, providing insights into the accuracy and applicability of the model in real-world scenarios. The outcomes of this research will contribute to a deeper understanding of TES systems, enabling the optimization of their design for specific heating demands.

KEYWORDS: Thermal energy storage, sensible heat, heat transfer fluid, energy geotechnics, sand battery.

1 INTRODUCTION

Sensible seasonal thermal energy storage (STES) technologies consisting of insulated storage tanks filled with water, sand, or rock are finding applications in water and space heating in residential communities. There is a need for experimental and numerical investigations to understand the performance of these systems with respect to the impact of tank size, filler material density, and heat transfer fluid (HTF) characteristics on efficiency and cost. The last two decades witnessed significant experimental efforts that were aimed at investigating heat transfer within thermal storage systems for the purpose of quantifying and optimizing their efficiency (Saitoh and Hirose 1986, Nallusamya et al. 2007, Mawire et al. 2010, Schlipf et al. 2015, Gaggioli et al. 2015, Cascetta et al. 2016, Al-Azawii et al. 2018, Gajbhiye et al. 2018, Lugolole et al. 2018, Kocak and Paksoy 2020, Advaith et al. 2021, and Zhang et al. 2021).

A laboratory-scale testing program is implemented in this study to investigate the thermal performance of a storage tank where the porosity of the filler and HTF type are varied. The experimental data is used to calibrate a numerical model in COMSOL to be used in future work to predict heat transfer mechanisms in full scale STES tanks. This research contributes to a deeper understanding of STES systems, enabling their optimization for specific heating demands.

2 EXPERIMENTAL SETUP

A schematic of the storage tank is shown in Figure 1. The tank (diameter = 30cm, height = 135cm) includes silica sand as the main storage filler and oil as the heat transfer fluid (HTF). Oil circulates through 55 steel pipes (diameter = 16mm) to inject and extract thermal energy from the tank, with the oil temperature controlled with a thermal control unit. The TES unit is designed to accommodate a storage capacity of 3 kWh of thermal energy. The instrumentation consists of 16 thermocouples: 7 thermocouples connected to the center and edge pipes at different depths, 7 thermocouples placed adjacent to the first group but within the sand, and 2 thermocouples located at the top and bottom oil collectors to measure the inlet and outlet temperature. The storage unit is insulated with two layers of 5cm rockwool with a density of 65 kg/m³. Table 1 summarizes the parameters varied in different experiments.

Table 1. Experimental Program

Exp. #	Mass Flow Rate (g/min)	Charge/ Discharge Time (hr)	Density (kg/m³)	HTF Type	T_H/T_L (ºC)	Eff. (%)
1	200	6/6	1450	Texatherm 32	130/20	67.4
2	400	6/6	1450	Texatherm 32	130/20	44.0
3	200	6/6	1450	Sunflower	130/20	68.1
4	200	6/6	1650	Texatherm 32	130/20	67.7

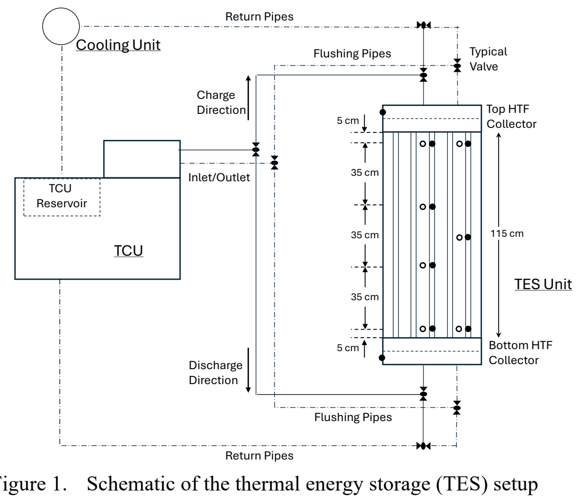

Figure 1. Schematic of the thermal energy storage (TES) setup

Figure 2 shows the experimental setup before and after insulating the tank. The setup comprises three main components: a thermal control unit, a thermal energy storage unit, and a cooling unit. The thermal control unit (TCU), manufactured by Julabo (model F25-HL), is a refrigerated/heating circulator designed to pump fluids at temperatures between 28°C and 200°C. The thermal energy storage (TES) tank manifests as a dual-media energy reservoir fashioned from galvanized steel. To ensure uniform flow of fluid within the pipes, two heat transfer fluid (HTF) collectors, positioned at opposite ends of the pipes, were provided. Each HTF collector is split into two compartments using a perforated plate in order to ensure a uniform flow of fluid in the pipes. The two HTF collectors at the terminals of the TES unit are needed to enforce a uniform temperature boundary condition. Before the initiation of the charging phase, the upper collector is flushed with hot HTF until the temperature of the oil in that compartment reaches T_H. Before the discharging phase, the lower collector is flushed with cold HTF until the temperature of the oil in the lower compartment reaches T_L. Flushing is achievable in both collectors through the use of two inlets/outlets that are placed at each collector to ensure that the desired temperature boundary conditions are achieved before the charging and discharging phases are initiated.

3 EXPERIMENTAL RESULTS

Figure 3 illustrates how temperature changes at the center pipe during Experiment 1. In the charging phase, heat gradually propagates from the top of the tank to the bottom, with the temperature rising steadily in both the oil inside the pipe and the surrounding sand. The readings from thermocouples 1 to 4, placed at different heights in the tank show a clear vertical temperature gradient and a noticeable time lag between each sensor's response—evidence of a slow-moving thermal front. What's also notable is how closely the temperatures inside the pipe match those in the nearby sand, indicating a very consistent heat distribution. By the end of the charging phase, roughly the upper third of the tank was fully heated, while the lower sections were still warming. While this might seem like a limitation, repeated charge–discharge cycles are expected to improve overall temperatures and storage efficiency.

During discharge, room-temperature oil was introduced through the bottom inlet of the TES tank. As seen in Figure 3, thermocouple 4 (located near the bottom) was the first to detect the discharge effect, with a rapid drop in temperature. This was followed sequentially by thermocouples 2, 3, and finally 1. By the end of the sixth hour, some heat still remained stored in the tank. If multiple charge/discharge cycles were used and heat losses between them minimized, this residual heat could accumulate, leading to improved system efficiency.

The effectiveness of the TES system is measured by quantifying its efficiency (μ) (Equation 1) with T_f being the fluid temperature exiting the TES tank, T_H the fluid temperature exiting an ideal thermocline tank filled with hot HTF, T_L the fluid temperature entering a TES tank, and $t_{discharge}$ the time of the discharge. If an HTF can be withdrawn at the same temperature at which it had been stored, the system has the highest efficiency (Bejan 2006). As such, the efficiency of a TES is dependent on the properties of the storage medium, the heat transfer fluid, and the geometric, structural, and insulation properties of the thermal storage tank.

$$\mu = \frac{\int_0^{t_{discharge}} (T_f - T_L)\,dt}{(T_H - T_L).t_{discharge}} \quad (1)$$

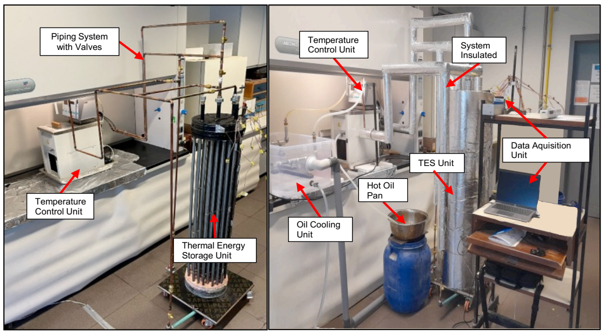

Figure 2. Experimental setup before and after insulation of the tank

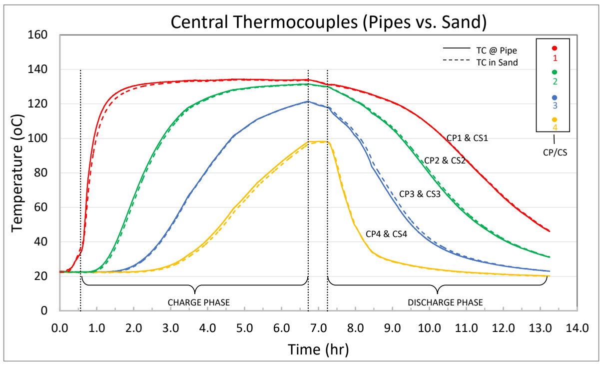

Figure 3. Temperature variation at the center pipe for Experiment 1

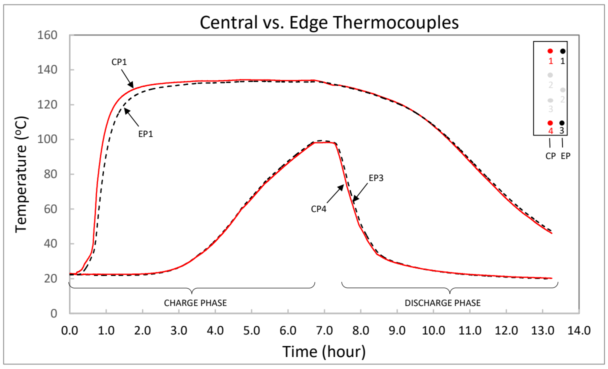

Figure 4. Comparison between center pipe and edge pipe temperature

One key factor in designing TES tanks is ensuring that heat transfer occurs in a one-dimensional (1-D) manner. Figure 4 compares the temperature readings from thermocouples located in the center and edge pipes at the same vertical height. As shown, the temperature profiles in both pipes remained nearly identical throughout all stages of the experiment. This suggests that the oil circulated evenly across all 55 pipes, maintaining a uniform temperature at each horizontal plane.

A comparative investigation was conducted on the thermal energy storage (TES) tank, examining the effect of key parameters on its thermal performance. Table 1 summarizes the parameters of four experiments that were conducted using the TES setup and the associated resulting efficiencies. The parameters are (1) the mass flow rate of the circulating HTF (200 and 400 g/min), (2) the filler density (loose versus dense sand), and (3) the type of HTF (Texatherm 32 versus sunflower oil). The aim is to quantify the impact of sand densification and the use of sustainable alternatives to synthetic oils on the thermal efficiency of the TES system. Abu-Hamdeh (2003) demonstrated that the densification of sand enhances its thermal properties while Mawire et al. (2016 and 2021) showed that the use of sunflower oil is a viable option in TES units. The availability of sunflower oil, its sustainability, and its lower price provide a competitive advantage over synthetic oil.

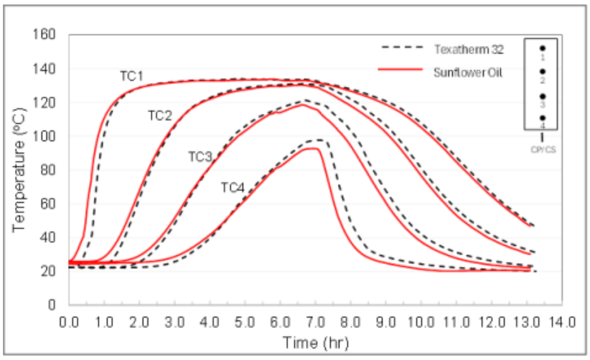

Figure 5. Comparison between Texatherm32 and Sunflower oil

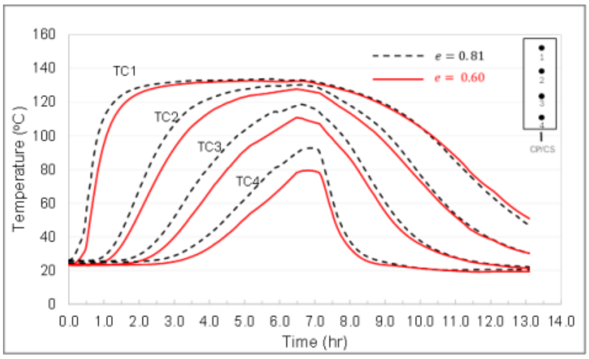

Figure 6. Effect of soil densification on temperature variation

The first study evaluates the impact of the heat transfer fluid by comparing Texatherm 32 with sunflower oil, while the second explores the effect of porosity by altering the sand void ratio from 0.81 to 0.60, highlighting the influence of packing density on energy storage and transfer. Figure 5 and Figure 6 summarize the results. As shown in Figure 5, replacing the synthetic oil with sunflower oil has only a minor effect on overall TES performance, with a slight advantage for Texatherm 32. However, this cannot be considered as conclusive as many factors need to be accounted for such as the availability of the product, its cost and its stability for long-term use. Figure 6 illustrates the influence of sand void ratio, showing that denser sand requires more thermal power to reach the same temperatures as looser sand. Nonetheless, under cyclic operation, this trend could reverse, potentially favoring the denser sand for repeated charging and discharging.

The efficiencies of the TES units for the four experiments conducted in this study are presented in Table 2. Results indicate efficiencies in the order of 68% for the tests conducted with a mass flow rate of 200 g/min, irrespective of type of oil and sand density. The temperature readings from the thermocouples at the top of the tank are the best indicator of the temperature of the fluid that is exiting the tank during discharge. In fact, the areas under the discharge curves representing the reduction in temperature of the upper thermocouple with time during the discharge phases are direct indicators of the efficiency of the TES unit. In an ideal thermocline with 100% efficiency, the HTF exiting the tank is expected to be at 130 ºC throughout the discharge period of 6 hours (a theoretical hypothetical flat curve at 130 ºC during discharge). As observed in Figures 3 to 6, the actual discharge curves for the real TES unit are not flat. In fact, the ideal discharge HTF temperature of 130 ºC is only achieved for a small time period after which the discharge HTF temperature drops indicating lower than ideal efficiencies. It is clear that all tests deviated from the response of an ideal thermocline which negatively affects the efficiency of the TES unit. The design of the tank (dimensions, number of tubes, diameter of tubes) may need to be revised to increase the thermal efficiency of the TES system.

4 NUMERICAL MODEL

In parallel to the lab experiments, a numerical 3D model of the tank was built in COMSOL Multiphysics as shown in Figure 7. The model was used to compare experimental and numerical results. Given the complexity of heat transfer and fluid dynamics within the tank, numerical modeling is essential for predicting the thermal behavior of the storage tank under various operating conditions to ensure an optimized design as well as provide insights into efficiency and feasibility for larger scale heating applications.

The modeling process involved building a detailed 3D representation of the thermal storage tank. Inside the tank, 55 pipes were uniformly distributed as per the arrangement in the experimental tank to distribute heat efficiently throughout the system. To further model the realistic path of movement of the HTF, the tank was partitioned into a top and bottom compartment, each divided into two sections with a steel plate in between the partitioned sections contains perforations (1.5 mm radius) to allow oil to distribute evenly to the pipes underneath. Thermal insulation was also modeled to reflect the laboratory experimental setup. Specifically, rockwool insulation was applied around the tank and at the top, while plywood was used at the bottom. This setup replicated the physical thermal boundaries and allowed the simulation to account for realistic heat losses to the environment. Due to the model's complexity and to maintain computational efficiency, the full-scale model was geometrically optimized using a symmetry plane. This allowed the simulation to be conducted on a half-scale model as shown in Figure 7.

In the numerical model, heat transfer in solids and fluids was coupled with laminar flow to capture the full thermal behavior of the system. Table 2 lists the thermal properties of the materials used in the model. Since the properties of the circulating oil vary with temperature, T_f, suitable linear and hyperbolic fits were applied to the limited data provided by the soil manufacturer. Laminar flow and heat transfer parameters from Table 2 (Experiment 1) were adopted in the COMSOL model. Using the halved model reduced simulation time from approximately 18 hours (full model) to 9 hours (half model), while preserving the accuracy and integrity of the physical system representation. This optimization allowed efficient modeling of multiple scenarios, making iterative improvements feasible within reasonable time limits.

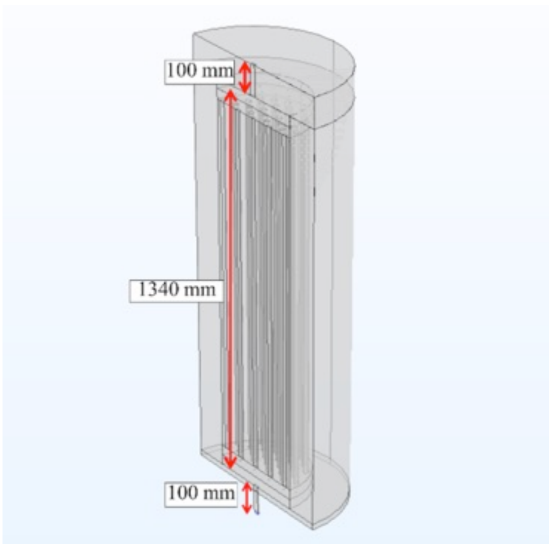

Figure 7. COMSOL model of the TES tank

To capture the complete thermal cycle of the system, two time-dependent studies were defined. The first study modeled the charge phase from 0 to 6.15 hours where hot oil entered from the top and exited at the bottom, storing thermal energy within the tank. The second study simulated the discharge phase from 6.15 to 12 hours where the flow direction was reversed, with oil entering from the bottom and exiting from the top to extract stored heat. The study durations were based on the experimental tests. Moreover, the model was further validated using an additional experimental run conducted at a higher flow rate of 400 g/min (experiment 2 in Table 1). This dual-validation approach ensured robustness in the model by verifying its accuracy under different operational conditions.

To evaluate how heat propagates throughout the tank during the charge phase, Figure 8b displays multiple 2D planes at different heights of the TES tank at 3 hours into the charging phase, showing the temperature variation along the tank's height. This visualization offers a clear spatial representation of the thermal front, highlighting how heat enters from the top and gradually moves downward over time. One of the key strengths of the COMSOL model is its ability to capture this dynamic progression, allowing the determination of how much of the tank has been thermally charged at any given moment.

The image clearly shows high temperatures (red regions) at 130 °C near the top inlet where hot oil is introduced, with a gradual gradient toward cooler areas (blue and green) near the bottom. This confirms that the charging process proceeded as expected, with heat propagating steadily from top to bottom. The model illustrates the role of the 55 pipes in facilitating efficient heat transfer. The heat visibly radiates outward into the surrounding sand medium, which acts as the primary storage material. The smooth color gradients in the sand indicate effective heat conduction and minimal thermal losses. This demonstrates that the current design ensures both deep and even penetration of heat, supporting long-duration energy storage and confirming the functionality under operating conditions.

Figure 8c presents a 2D plane cut at tank mid-height taken during the charging phase at 3 hours, showcasing the temperature distribution across the tank's cross-section. The image distinctly illustrates how the oil flowing through the 55 pipes effectively transfers heat to the surrounding sand medium. The high-temperature zones (in red) are concentrated around the pipes, indicating efficient heat conduction from the oil to the sand, while revealing a temperature lag between the fluid in the pipes and the surrounding sand of less than 10 °C. This thermal pattern confirms the system's design effectiveness in distributing heat evenly throughout the medium, avoiding localized hot spots. Additionally, the outer blue regions of the figure highlight the impact of the modeled insulation layer, which includes rockwool around the tank and at the top, and plywood at the bottom, accurately replicating the laboratory configuration. The cool color gradient near the boundaries indicates minimal heat leakage to the surroundings, validating the insulation performance and its role in preserving thermal energy within the system.

The COMSOL model was developed to closely replicate the experimental thermal energy storage (TES) system tested in the laboratory. The base model was initially modeled using experimental data for the case with a flow rate of 200 g/min. After extensive refinement—such as correcting symmetry boundary issues, incorporating realistic insulation (rockwool and wood), optimizing mesh resolution, and accurately setting material properties and flow conditions, the temperature evolution at four thermocouples placed along the central pipe is shown over the full cycle (flushing, charging, and discharging) as indicated in Figure 9 where the solid lines represent the COMSOL simulation, while the dotted lines reflect experimental measurements. The close alignment between the two sets of curves validates the accuracy of the numerical approach, especially in capturing both the heating and cooling dynamics of the tank. Notably, the model reliably predicted the temperature peaks during both the charge and discharge phases, confirming that the heat transfer and flow behavior in the simulation matched real-world observations.

To further assess the model's robustness and adaptability, the COMSOL model was modified to simulate a second experiment conducted at a higher flow rate of 400 g/min. As shown in Figure 10, the results again revealed strong agreement between the COMSOL predictions and experimental data, despite the change in the flow rate. This demonstrates that the model did not accidently model the base case model only, but could accurately simulate different experimental conditions.

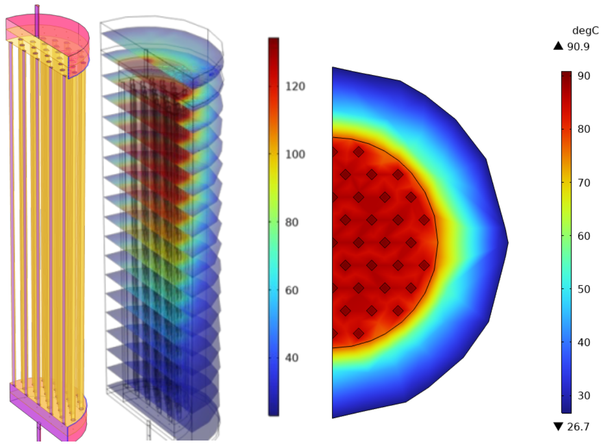

Figure 8. (a) COMSOL 3D model of the Tank, (b) temperature variation after 3hrs of charge, and (c) 2D section at mid-height showing temperature after 3hrs of charge

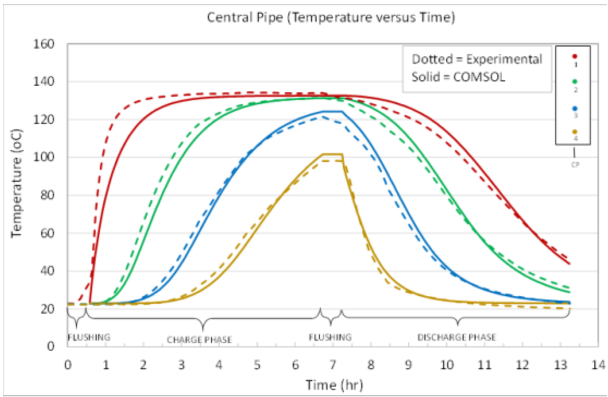

Figure 9. Comparison between COMSOL model and the results of Experiment 1 (Flow Rate = 200 g/min).

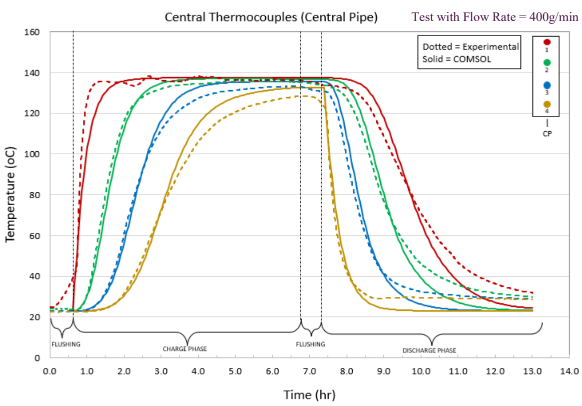

Figure 10. Comparison between COMSOL model and the results of Experiment 2 (Flow Rate = 400 g/min).

Table 2. Thermal Properties of Materials

	Steel	Texatherm 32	Sand
Density $\rho\ (kg/m^3)$	7850	-0.6695T+867.93	1450
Thermal Conductivity $k\ (W/m.K)$	44.5	-	0.3
Heat Capacity $C_p\ (J/Kg.K)$	475	3.586T + 1946.3	830
Dynamic Viscosity μ $(Pa.s)$	-	$\left(\frac{313 \times 10^{-6}}{1 - 0.00684\,T + 0.00566\,T^2}\right) \times (-0.6695T + 867.93)$	-

The COMSOL Multiphysics model successfully simulated the thermal and fluid dynamic behavior of the TES system with high accuracy and computational efficiency. The halved model symmetrically defined along the y-axis which was utilized for all simulations captured key thermal patterns and flow behavior in close alignment with experimental data for tests conducted at flow rates of 200 g/min and 400 g/min.

5 CONCLUSIONS

In this paper, a laboratory-scale experimental setup for a thermal energy storage "sand battery" was designed, constructed, and tested to showcase the effects of the HTF type, solid filler density, and thermal energy input on the performance and efficiency of the TES tank. 3D numerical models were also built in COMSOL to simulate the heat transfer within the sand battery.

Results of the experimental tests indicate that for an HTF mass flow rate of 200 g/min, even at the maximum charging time (6 hours), the sand did not reach its full thermal storage potential in the lower third of the tank. The same was observed at the end of the discharge phase in the upper third of the tank where the temperature was observed to remain above ambient even after 6 hours of discharge. Upon doubling the mass flow rate of the HTF (doubling the input thermal energy), the rate at which the temperature of the sand increased or decreased during the charging and discharging phases, respectively was evidently higher. However, the fast HTF flow rate resulted in reductions in the total thermal efficiency of the TES unit compared to the tests conducted at the lower flow rate. Replacing the synthetic Texastherm oil with a refined Sunflower oil led to the same thermal response in both the charging and discharging phases indicating the potential of using sustainable and cost-effective sunflower oils in applications involving thermal energy storage for heating. On the other hand, increasing the sand density resulted in a slightly lower maximum temperature in the sand during charging compared to the loose sand case. This indicates that the dense sand could have stored more energy had the thermal energy input been increased in the experiment.

The COMSOL simulations provided extensive insights into temperature distribution, velocity fields, and the overall thermal efficiency of the storage system. Ultimately, the finalized model served as a validated tool for understanding the thermal behavior of the TES system and laid the groundwork for future scale-up and implementation of similar systems in heating applications across Lebanon. This ability of the numerical model to generalize and accurately simulate thermal behavior under varied flow rates is essential, especially when planning for larger-scale applications. With such a validated and flexible model, different operational strategies can be tested virtually before real-life implementation, saving time, resources, and enhancing system design. The findings confirm that the developed COMSOL model is not only an accurate replica of the current laboratory setup but also a powerful predictive tool for future design, scale-up, and optimization of TES systems in real-world heating applications. In summary, the combination of experimental and modeling approaches provided a comprehensive understanding of the TES system's effectiveness, guiding further refinement and enabling the creation of a sustainable, reliable, and efficient storage solutions.

6 ACKNOWLEDGEMENTS

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