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Experimental Investigation of Direct Heated Rock Bed Thermal Energy Storage for Application in Small Scale Power Generation

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Abstract

Thermal energy storage is essential for power generation using renewable energy sources like solar and wind, addressing the intermittent nature of these resources and the fluctuating power demand by users. This study experimentally investigates using a new approach of direct heated packed rock-air bed thermal energy storage for small-scale power generation. The experimental setup comprised a cylindrical steel tank (6 mm thickness, 0.45 m diameter, 1.0 m height) with a 25 mm air gap and 200 mm (Castable, Refractory and Fiber glass) insulation. Two granite rock sizes (average diameters of 1.5 cm and 3.5 cm) were tested. An electric heat source maintained a temperature of approximately 550 °C at the bottom of the storage for charging, while thermocouples monitored temperatures at various positions. Thermal decay characteristics were studied under no-load conditions, and discharging was tested by circulating water through an embedded coiled pipe within the storage. During the first 10 h of charging, temperatures between 100 °C and 400 °C were achieved for both 1.5 cm and 3.5 cm rocks. For the 1.5 cm rocks, temperatures reached 400 °C at the bottom, 225 °C in the middle, and 115 °C at the top, while the 3.5 cm rocks reached 395 °C, 180 °C, and 93 °C, respectively. These results show that smaller rocks (1.5 cm) provided better thermal performance, reaching higher temperatures throughout the storage than larger rocks (3.5 cm). The system reached steady state in about 10 hours, after which heat transfer slowed due to the low thermal conductivity of the rocks, with conduction as the dominant mode. During discharging without load, the 3.5 cm rocks cooled to near ambient within 40 hours, while the 1.5 cm rocks maintained 75 °C over the same period. The storage fully discharged within two days, while water circulation at 25 L/h produced steam for 5 h before temperatures dropped below boiling for the smaller rock size. Significant heat losses from all surfaces highlighted the need for better insulation. Overall, the study demonstrates the potential of packed air-rock bed thermal energy storage for small-scale applications, with recommendations to apply forced convection and improve insulation to enhance efficiency.

1. Introduction

Thermal energy storage (TES) systems have been extensively studied as a key technology for harnessing renewable energy or utilizing waste heat resources [1-4]. This is because the conversion into thermal energy is the easiest and widely accepted method [3]. Generally, there are three types of TES systems: sensible, latent and thermo-chemical [5-8]. In some cases, it can be stored in hybrid systems such as combined sensible and latent heat storage [9, 10]. In most cases, the required temperature of an application decides the selection of the right storage material [11]. When air is used as a heat transfer medium, packed rock bed systems are inexpensive, safe and can be operated at very high temperatures [3]. A rock bed thermal energy storage system is considered to store solar energy for multi-purpose applications.

Packed air rock bed TES is commonly considered as a separate unit having a circulating heat transfer loop with the heat absorber in a solar concentrator or heat source. This makes the system somewhat complex, requiring high-quality insulation of the heat transfer system as well as flow control devices, as shown in Figure 1 [8, 12].

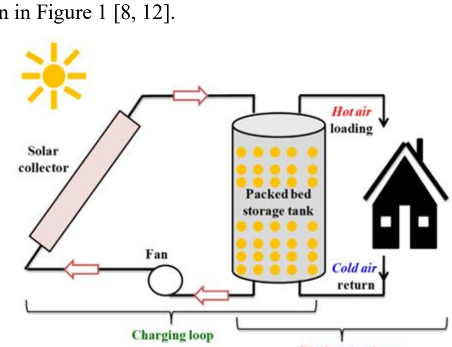

Figure 1: Packed bed TES with charging and discharging loops [8].

Furthermore, in most of the previous studies related to TES, packed bed thermal energy storage systems rely on thermoclines, distinct boundaries with concentrated temperature gradients, for efficient energy storage, as shown in Figure 2. Experimental studies in this field focus on enhancing and stabilizing these thermoclines by optimizing the system's design and operating conditions, thereby improving energy storage efficiency and minimize thermal losses during the charging and discharging phases [13-15].

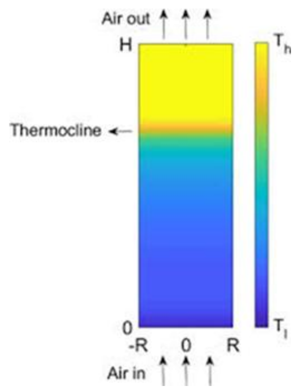

Figure 2: The thermocline, a distinct boundary with a concentrated temperature gradient, is a key characteristic of packed-bed thermal energy storage systems [15].

To the best of the authors' knowledge, there is limited research on the performance of directly heated packed rock bed thermal energy storage technologies. This new approach reduces system complexity by eliminating the need for connections and heat exchanger devices between the heat source and the storage unit. Furthermore, it avoids the challenge of maintaining a thermocline, which would otherwise require keeping high temperatures at a specific location within the TES.

A thermal energy storage system can use different sources of heat, such as solar energy or waste heat. Figure 3 shows a basic diagram of a directly heated thermal energy storage system. The diagram helps to explain the main parts of the system and how they work together to charge and discharge the stored heat.

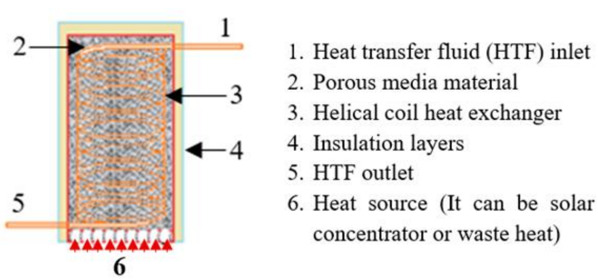

Figure 3: A simplified diagram of a directly heated thermal energy storage system, showing the major components involved in storing and extracting heat.

Most previous studies on thermal energy storage (TES) have relied on conventional approaches, where the rock bed is heated indirectly from the top and the discharging process is carried out using external heat exchangers. However, these methods often result in higher heat losses and require more complex system components. This study addresses these gaps by directly heating the rock bed from the bottom, allowing heat to rise naturally through the storage. In addition, the discharging process was performed using a helical coiled tube embedded within the TES (Figure 3), which reduces heat loss during energy extraction compared to external systems. Another gap in earlier work is the limited investigation of natural convection as a heat transfer mechanism. In this study, heat transfer within the rock bed was examined under both natural and forced convection conditions to evaluate whether natural convection alone can provide sufficient thermal performance for practical applications. This approach could simplify system design by reducing the need for auxiliary components such as fans. The experimental work also provides new insights by analyzing the charging and discharging characteristics of the TES using two different rock sizes. Furthermore, the performance was studied under two discharging modes: with load (using water) and without load. Together, these contributions make the study distinct from conventional approaches and provide valuable guidance for improving direct-heated TES systems.

Crushed granite rocks were used as the storage material in this experimental study. Granite, an igneous rock, has been widely studied as a promising option for thermal energy storage systems because of its good thermal and mechanical properties. It has a specific heat capacity of about 780 J/(kg·K), a compressive strength between 110-170 MPa, and can endure temperatures of several hundred degrees Celsius. Its chemical stability and resistance to corrosion also enhance the safety and durability of rock bed storage systems. In addition, granite is low-cost, widely available, and has favourable thermal characteristics such as high heat capacity and density [3, 16-19]. Li and Ju [20] reported that granite is a suitable thermal energy storage material for concentrated solar power (CSP) systems, as it stayed stable even after repeated exposure to high-temperature cycles. Moreover, this type of rock is abundantly available near the experimental study site.

2. Materials and methods

2.1. Experimental set-up description

Two vertically configured concentric cylinders made of stainless steel have been used to construct the container for the thermal energy storage experimental set-up. The internal diameter and height of the TES are 0.45 m and 1.0 m, respectively. The air gap between the concentric cylinders is 2.5 cm. The TES was insulated with three layers of insulation materials (Figure 4). A helically coiled copper tube was embedded inside the storage container. This was used to extract the stored heat in the TES through a circulating heat transfer fluid (HTF). An electrical heat source was used at the bottom of the storage. K-type thermocouples were installed along the storage (axially and radially) at different positions (at an interval of 12 cm from bottom to top) to measure temperature distribution (Figure 5). Three data loggers (USB TC-08 loggers and PicoLog 6 software) were connected with the thermocouples to record the temperature inside the storage. Details of the insulation materials used for the experiment are described in Table 1.

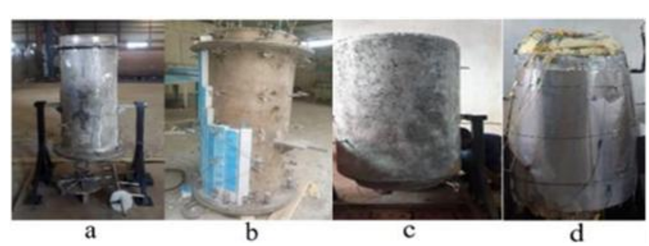

Figure 4: Thermal energy storage (TES) constructed with different insulation materials: a) TES without insulation, b) TES with refractory insulation, c) TES with Castable insulation over refractory, d) TES with fiberglass insulation over Castable insulation.

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Table 1. Insulation materials properties.

No	Insulation material type	Insulation material specific name	Insulation material specification		References
			Thermal Conductivity	Thickness used	
1	Castable insulation	Solcasting (CARSIT SOL M 10-6)	1.84 W/m.K at 400 °C, and 1.77 W/m.K at 800 °C.	10 cm	(Scribd, accessed Oct 18, 2023)
2	Refractory insulation	Refractory light weight insulation material (Refratherm (R) 150)	0.5 W/m.K at 300 °C and 0.6 W/m.K at 700°C.	5 cm	(Refra, accessed Oct 18, 2023)
3	Fiber glass insulation	Fiber glass blanket	0.032-0.07 W/m.K (255-475 °C)	5 cm	(Engineering Toolbox, accessed Oct 18, 2023)

Table 2. TES Dimensional and Operational Parameters.

A	Dimensional parameters	Values	Units	Reference
1	TES container height	1.0	m	
2	TES container diameter	0.45	m	
3	Surface area	1.78	m^2	
4	Average rock sizes	0.015 & 0.035	m	
5	TES container volume	0.125	m^3	
6	Porosity	0.35	-	
B	**Operational parameters**			
1	Temperature of heat source	550	°C	
2	Ambient temperature	25	°C	
3	Rock density	2648	kg/m^3	
4	Specific heat of rock	820	J/kg K	[21]
5	Conductivity of rock	2.8	W/m K	

After completing the thermal design calculations to size the storage tank for generating 1 kW of electrical power, the thermal energy storage system was built. The assumptions used, along with the calculated dimensions and operating parameters, are summarized in Table 2.

In the experimental setup, an electrical heater was installed at the bottom of the thermal energy storage (TES) unit to act as the heat source. To record the temperature distribution inside the storage bed, a vertical rod fitted with thermocouples was centrally mounted, extending from the bottom of the unit to the top. This allowed continuous measurement of the temperature profile along the height of the TES. As shown in Figure 5, a total of 16 thermocouples were placed at specific points in both the radial and axial directions. The axial arrangement allowed tracking of the heat front along the height of the storage, while the radial arrangement measured how heat spread from the center to the walls. This setup was designed to record temperature changes in all key directions, providing detailed evaluation of heat transfer and overall thermal performance of the TES.

Additional thermocouples were installed on the outer surface of the TES to measure heat loss through the insulation. A temperature controller was used to keep the heat source constant at about 550 °C. After positioning the thermocouples, the TES was filled with crushed granite rocks (Figure 7). Two different rock sizes, with average diameters of 1.5 cm and 3.5 cm, were used during the experiments (Figure 8). All thermocouples were connected to data loggers, which continuously measured and recorded the temperature at different locations inside the TES (Figure 6).

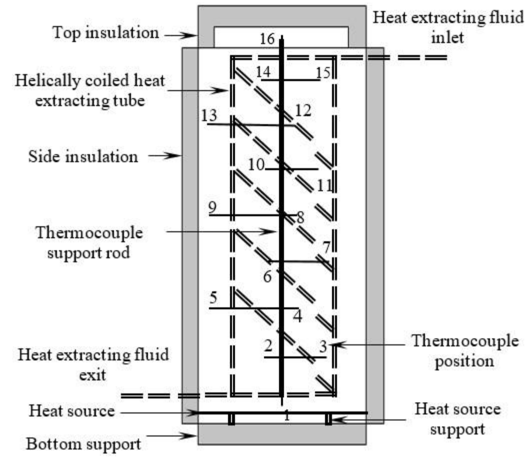

Figure 5: TES components and position of thermocouples.

Figure 6: Experimental set up of the TES (Natural convection).

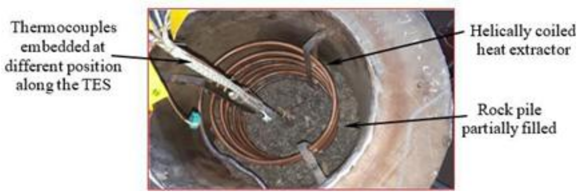

Figure 7: Internal part of the TES before fully filling the rock piles

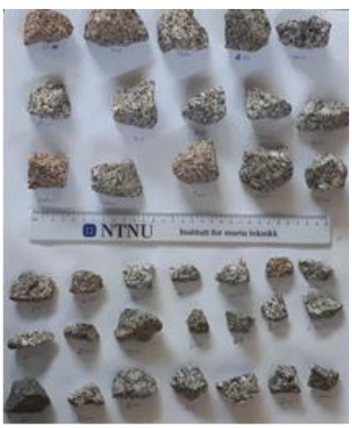

Figure 8: Two sizes (1.5 cm and 3.5 m average diameters) of crashed rock ready for experiment.

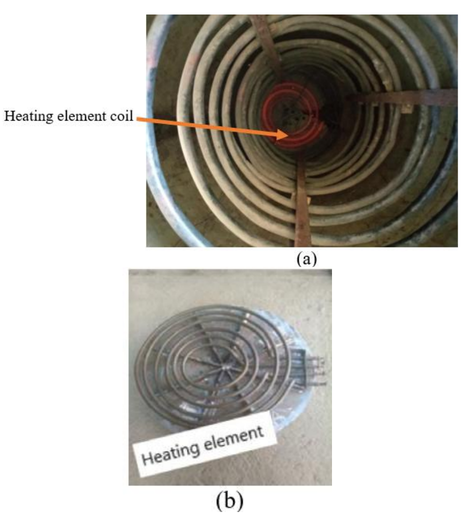

Figure 9: Pictorial illustration of electrical coil heating element (a) at the bottom of the TES for checkup before filling the granite rocks (b) before assembled with the TES and set on top of its seat structure.

An electric heating element was used as the heat source in this experimental study, as shown in Figure 9. The element can reach temperatures of up to 600 °C and is designed as a coiled tube with an outer tube diameter of 12 cm and a nominal coil diameter of 35 cm. K-type thermocouples were fixed on its surface to measure the temperature. These thermocouples were connected to a PID type temperature controller that operated the electrical contractor, switching the heater on and off between 540 °C (lower limit) and 560 °C (upper limit). This setup allowed the heating element to maintain a stable temperature within the set range. The discharging process of the TES was carried out in two modes: without load and with load. In the no-load test, the heater was switched off to study the thermal decay and heat losses from the storage unit. In the load test, an 80-liter water tank was placed 1.5 meters above the TES and connected to a helical coiled tube embedded inside the storage (Figure 10). The water flow rate was measured using a rotameter, while a gate valve was used to keep the flow constant at 25 liters per hour (0.007 kg/s).

Figure 10: The water reservoir used during the discharging phase of the thermal energy storage (TES) system. This reservoir, positioned above the TES, supplied the water that was heated by the stored thermal energy.

Figure 11: TES discharging with load using water.

A thermocouple was installed at the outlet of the heat-extracting pipe to measure the temperature of the outgoing generated steam leaving the system (Figure 11). The discharging process continued until the steam temperature dropped below a certain threshold, showing that the stored thermal energy was no longer able to produce steam.

3. Results and discussion

3.1. TES charging and discharging characteristics with no load

The TES system was continuously charged, and temperature measurements were recorded at various positions within the storage. Initially, the temperature increased rapidly, particularly during the first 20 hours, as illustrated in Figure 12. This rate of temperature rise gradually slowed down and eventually flattened, showing no significant further changes. This suggests that the initial impact of natural convection, driven by the temperature gradient, influenced heat transfer during the early stages of charging. Over time, this effect decreased, and heat transfer was mainly by conduction. Because rock has a naturally low thermal conductivity, the temperature rise became slower. This agrees with the findings of Jalalzadeh-Azar, et al [22], who reported that thermal radiation and intraparticle conduction play only a minor role in the overall heat transfer of packed-bed sensible heat storage. At the bottom of the storage (12 cm from the base), the temperature reached 400°C after approximately 15 hours. In the middle section of the storage (48 cm from the base), the temperature achieved 225°C after 50 hours. The top of the storage reached 100 °C after 35 h of charging and continued to rise to approximately 125 °C at the 55 h mark when heating ceased it then starts to decline.

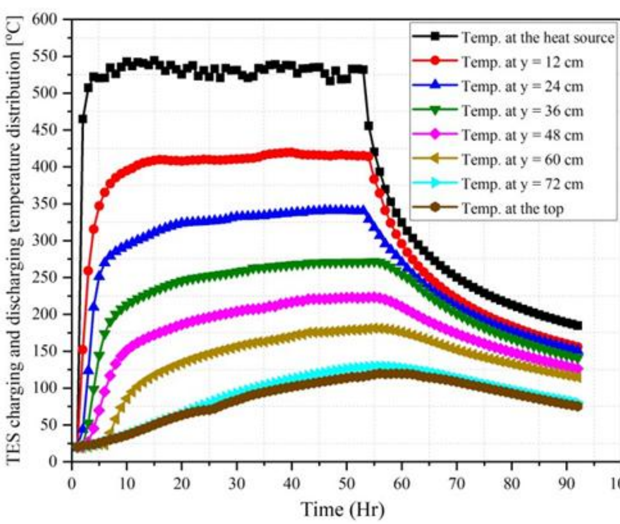

Figure 12: Temperature distribution along the height of the thermal energy storage system (1.5 cm average rock size).

Despite utilizing three layers of insulation during the experiment, significant heat loss was observed at the bottom of the storage unit, where the electric heater was positioned (Figure 13). This occurrence can be attributed to the conduction of heat through the base of the heater and the surrounding storage material. The rate of heat loss was found to be directly proportional to the temperature gradient between the heater and the ambient environment. Such heat loss considerably impacts the system's overall efficiency, emphasizing the need to address this factor during both the design and operational stages of similar systems.

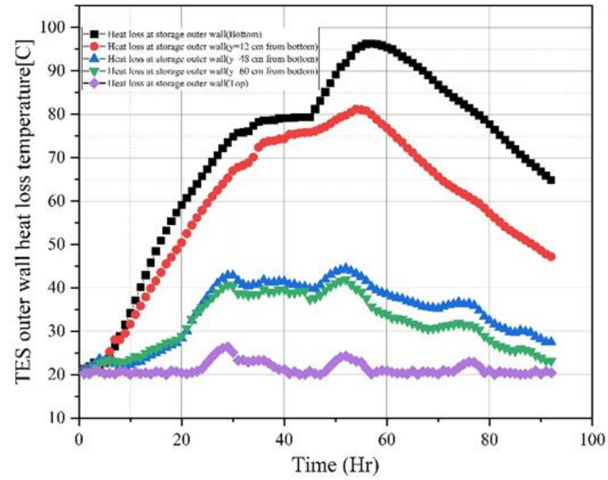

Figure 13: Variation of temperature over time showing the heat loss behavior of the storage filled with 1.5 cm rock size.

Figure 14 illustrates the temperature distribution during the charging and discharging processes for rocks with an average size of 3.5 cm. Similar thermal behavior was observed for rocks of this size. Free convection played a significant role in the initial 15 hours, greatly enhancing the temperature increase throughout the storage unit. However, this effect diminished over time, resulting in a marked reduction in the rate of temperature rise. The maximum temperature recorded near the heat source was 395°C, while the peak temperature at the top of the storage reached about 100°C. After 30 hours, no further temperature increase was noted, indicating that the system had reached an equilibrium point. In contrast, the smaller rock sizes showed a slight temperature increase throughout the charging process. This steady state was attributed to substantial heat loss from the thermal energy storage system, as shown in Figure 15.

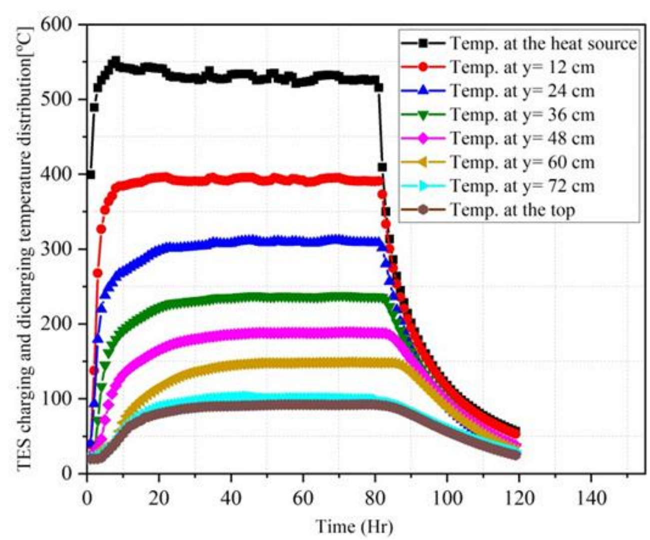

Figure 14: Temperature distribution along the height of the thermal energy storage system (3.5 cm average rock size).

Table 3: Comparison of Previous Studies with the Present Findings.

Study	Rock Type/Material	System Configuration	Max Temperature (°C)	Charging Time	Discharging Performance	Storage Efficiency	Key Findings
Present Work (1.5 cm granite)	Granite (1.5 cm avg)	Direct heating, vertical	400 (bottom), 225 (middle), 125 (top)	10 hours for the system to reach steady-state condition	The system reached equilibrium after about 55 hours under no-load condition., With a load condition of 25 l/h, the system generated steam for about 5 hours.	Not quantified (heat losses significant)	Smaller rocks better performance, During the charging phase, natural convection is dominant at the beginning, while conduction becomes dominant later.
Present Work (3.5 cm granite)	Granite (3.5 cm avg)	Direct heating, vertical	395 (bottom), 180 (middle), 100 (top)	10 hours for the system to reach steady-state condition	The system reached equilibrium after about 30 hours under no-load condition.	Not quantified (heat losses significant)	Similar behavior, slightly lower temperatures than 1.5cm
(Marongiu, Soprani and Engelbrecht, 2019)	Swedish Diabase (5 mm, 15-40 mm)	Horizontal flow, 450 kWhth	600° C	6 hours (80% SOC)	• Heat is extracted by reversing airflow through the bed • Discharge efficiency and heat losses were significantly affected by rock size; larger sizes increased outlet heat losses due to buoyancy effects.	Vary between 69% and 96%	• Smaller rock sizes and higher air flow rates improve the charging efficiency, with charge efficiencies in the range of 69% to 96%. • The heat capacity of insulation layers can negatively affect the performance of small-scale rock bed storage systems, making insulation design critical for optimizing efficiency.
(Bruch *et al.*, 2014)	Natural rocks (Silica rocks and Silica sand)	Dual-media thermocline TES (Vertical orientation)	600-700° C	N.A	The discharging performance highlights the system's reliability and efficiency, with a high energy extraction rate and stability under varying conditions, making it suitable for integration into CSP power plants.	89% useful energy extraction during discharge, but this is not a comprehensive efficiency metric (e.g., it excludes charging losses)	Dual-media thermocline TES as a cost-effective, stable, and scalable option for CSP applications, with the experimental setup and numerical model providing a solid foundation for further optimization.
(Muhammad *et al.*, 2023)	Swedish Diabase (8-12 mm)	Vertical flow	600° C	24 hours	• During discharging, cold air is blown vertically from the bottom of the rock bed, opposite to the charging flow.	77% to 94% during the charging phase	• Smaller rock size improved heat transfer but increased pumping power. • The validated CFD model accurately predicted temperature and efficiency, enabling scale-up to 330 MWh for solar thermal applications.
(Knobloch *et al.*, 2022)	Diabase	Vertical flow rock bed	675 °C	10 hours	• After charging (hot air blown downward), the airflow direction is reversed for discharging. • TES discharged with very high efficiency (>95%) and stable temperature output over the expected duration	Initial round-trip efficiency 70.7%. first law round-trip efficiency increases to 80.7%.	• The round-trip efficiency of the thermal energy storage (TES) system with a packed rock bed can be as high as 80.7%. • Diabase rocks from Sweden were identified as an effective, low-cost storage material.
(Esence *et al.*, 2019)	Basaltic rocks	vertical	800° C	N.A	Variable performance	Variable with conditions	High temp operation demonstrated
(Gerstle *et al.*, 2023)	Pea gravel	Radial packed bed	550° C	4 hours	• Thermocline degradation • Effective discharge of stored thermal energy	Round-trip exergy efficiency, estimated around 90% for scaled-up systems	• The development and degradation of the thermocline • Heat losses during storage phase were measured and modeled, showing the importance of insulation and thermal management.

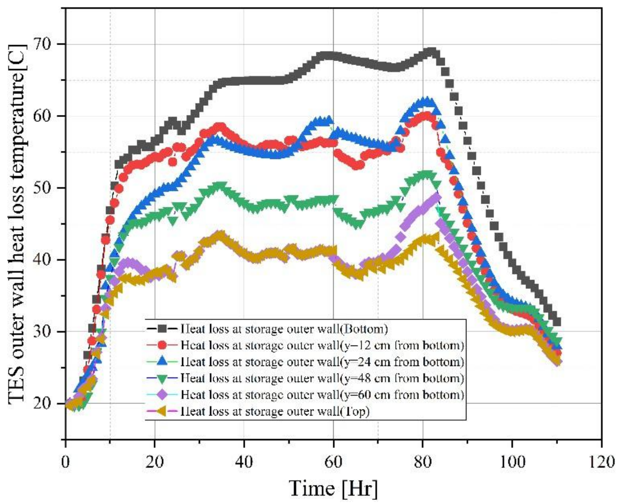

Figure 15: Variation of temperature over time showing the heat loss behaviour of the storage filled with 3.5 cm rock size.

As shown in Figures 12 and 14, the storage filled with 1.5 cm rocks reached temperatures of about 400 °C at the bottom, 225 °C in the middle, and 115 °C at the top. For the 3.5 cm rocks, the corresponding temperatures were around 395 °C, 180 °C, and 93 °C. These results show that smaller rocks achieved slightly better heat transfer and storage performance compared to larger rocks. This observation agrees with the findings reported by Marongiu et al. [23].

3.2. TES Charging and Discharging Characteristics with load

Figure 16 shows the temperature distribution during the discharging phase with water. This phase started once the heat source was switched off. Before discharging, the bottom of the storage reached about 400 °C, the middle was around 150 °C, and the top was close to 100 °C. The discharge was carried out at a water flow rate of about 25 L/h, which was measured by the rotameter and controlled with the gate valve.

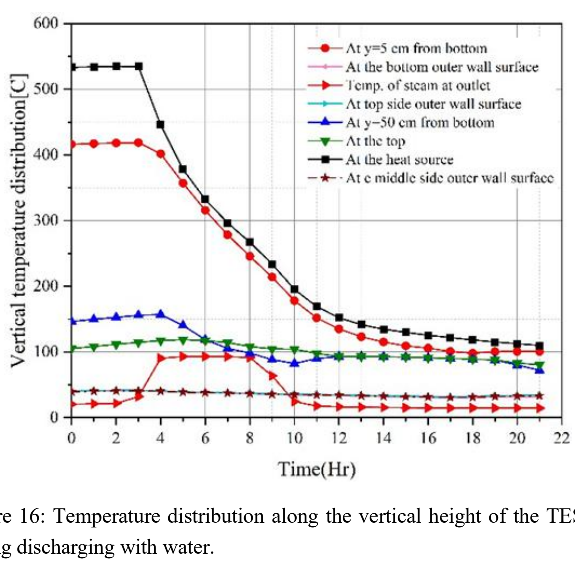

Figure 16: Temperature distribution along the vertical height of the TES during discharging with water.

A steady steam temperature of about 92 °C was recorded, which matches the boiling point of water at Mekelle's altitude (2200 m). As shown in Figure 16, the outlet pipe temperature rose to the boiling point as steam was released. Continuous steam production was maintained for nearly five hours. During this time, the storage temperature gradually decreased as energy was drawn out. By the end of the five hours, the bottom temperature had dropped to around 250 °C, while the middle and top temperatures settled at about 100 °C.

4. Conclusions

The experimental study showed that the charging process took a long time for both rock sizes. This extended duration was primarily due to the experimental setup, where power input was regulated to maintain a constant temperature, prevent overheating of the thermal components. The findings further indicated that, aside from the early stage dominated by natural convection, conduction was the main heat transfer mechanism. This slow process can be attributed to the inherently low thermal conductivity of rocks. Significant heat losses were also observed from all surfaces. For the 1.5 cm size rocks, temperatures of 400, 225 and 115°C were achieved at the bottom, middle and top of the storage, respectively. For 3.5 cm size rocks, corresponding temperatures were 395, 180 and 93°C. This suggests a slight performance advantage for smaller rocks over larger ones.

During the discharge process without load, a rapid temperature drop was recorded, highlighting considerable heat loss from the surfaces. The storage temperature fell to approximately 100°C within two days. In contrast, the discharge process with load, which involved water circulation, produced steam for about five hours. These results indicate the necessity of measures to enhance the charging rate. Incorporating forced convection is essential to accelerate the charging process, and improvements in insulation are also required to minimize heat loss. This type of TES system can also be considered for alternative uses, such as clean cooking applications using the generated steam.

Acknowledgments

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References

1. Isao, K.; Swapan, K. Chaudhuri. The structure of maesaquinone. Bioorganic and Medicinal Chemistry Letters. 1994, 4(9), 1131-l 134.
2. Bryan, R. M.; Sevim, Z. E. Synthesis and Evaluation of a Series of α-Hydroxy Ethers Derived from Isopropyl Oleate. J. Amer Oil Chem. Soc, 2006, 83(11), 959–963.
3. Mulugeta, T.; Legesse, A.; Yinebeb, T.; Diriba, M.; Shiferaw, D. Isolation of compounds from acetone extract of root wood of Moringa stenopetala and evaluation of their antibacterial activities. Res. J. Medic. Plants. 2013, 7:32-47

[1] I. Dincer, M.A. Rosen, Thermal energy storage: systems and applications, John Wiley & Sons2011.

[2] A. Gil, M. Medrano, I. Martorell, A. Lázaro, P. Dolado, B. Zalba, L.F. Cabeza, State of the art on high temperature thermal energy storage for power generation. Part 1—Concepts, materials and modellization, Renewable and sustainable energy reviews 14(1) (2010) 31-55.

[3] H. Singh, R. Saini, J. Saini, A review on packed bed solar energy storage systems, Renewable and Sustainable Energy Reviews 14(3) (2010) 1059-1069.

[4] M. Hänchen, S. Brückner, A. Steinfeld, High-temperature thermal storage using a packed bed of rocks–heat transfer analysis and experimental validation, Applied Thermal Engineering 31(10) (2011) 1798-1806.

[5] M.E. Navarro, M. Martínez, A. Gil, A. Fernández, L.F. Cabeza, R. Olives, X. Py, Selection and characterization of recycled materials for sensible thermal energy storage, Solar Energy Materials and Solar Cells 107 (2012) 131-135.

[6] S. Khare, M. Dell'Amico, C. Knight, S. McGarry, Selection of materials for high temperature sensible energy storage, Solar Energy Materials and Solar Cells 115 (2013) 114-122.

[7] L. André, S. Abanades, Recent advances in thermochemical energy storage via solid–gas reversible reactions at high temperature, Energies 13(22) (2020) 5859.

[8] R. Mabrouk, H. Naji, A.C. Benim, H. Dhahri, A state of the art review on sensible and latent heat thermal energy storage processes in porous media: mesoscopic simulation, Applied Sciences 12(14) (2022) 6995.

[9] H.P. Garg, S.C. Mullick, V.K. Bhargava, Solar thermal energy storage, Springer Science & Business Media2012.

[10] D. Okello, C.W. Foong, O.J. Nydal, E.J. Banda, An experimental investigation on the combined use of phase change material and rock particles for high temperature (∼ 350 C) heat storage, Energy conversion and management 79 (2014) 1-8.

[11] O.E. Ataer, Storage of thermal energy, Energy storage systems 1 (2009) 97.

[12] D. Okello, Rock bed thermal energy storage for solar cooking application (Potential for solar cooking in Uganda), 2012.

[13] M. Cascetta, F. Serra, G. Cau, P. Puddu, Comparison between experimental and numerical results of a packed-bed thermal energy storage system in continuous operation, Energy Procedia 148 (2018) 234-241.

[14] T.R. Davenne, S.D. Garvey, B. Cardenas, J.P. Rouse, Stability of packed bed thermoclines, Journal of Energy Storage 19 (2018) 192-200.

[15] A. Soria-Verdugo, J. Guil-Pedrosa, F. Hernández-Jiménez, L. García-Gutiérrez, E. Cano-Pleite, N. García-Hernando, Experimental analysis of a novel confined bed system for thermal energy storage, Journal of Energy Storage 69 (2023) 107972.

[16] H.W. Fricker, High-temperature heat storage using natural rock, Solar energy materials 24(1-4) (1991) 249-254.

[17] K. Allen, T. Von Backström, D. Kröger, A. Kisters, Rock bed storage for solar thermal power plants: Rock characteristics, suitability, and availability, Solar Energy Materials and Solar Cells 126 (2014) 170-183.

[18] X. Shang, Z. Zhang, X. Xu, T. Liu, Y. Xing, Mineral composition, pore structure, and mechanical characteristics of pyroxene granite exposed to heat treatments, Minerals 9(9) (2019) 553.

[19] M. Nemś, A. Nemś, K. Gębarowska, The influence of the shape of granite on the heat storage process in a rock bed, Energies 13(21) (2020) 5662.

[20] B. Li, F. Ju, Thermal stability of granite for high temperature thermal energy storage in concentrating solar power plants, Applied Thermal Engineering 138 (2018) 409-416.

[21] I. Sarbu, C. Sebarchievici, A comprehensive review of thermal energy storage, Sustainability 10(1) (2018) 191.

[22] A. Jalalzadeh-Azar, W. Steele, G. Adebiyi, Heat transfer in a high-temperature packed bed thermal energy storage system—roles of radiation and intraparticle conduction, (1996).

[23] F. Marongiu, S. Soprani, K. Engelbrecht, Modeling of high temperature thermal energy storage in rock beds–Experimental comparison and parametric study, Applied Thermal Engineering 163 (2019) 114355.