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Published in:
Journal of Energy Storage

DOI:
10.1016/j.est.2024.111350

Published: 10/05/2024

Document Version
Publisher's PDF, also known as Version of record

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Please cite the original version:
Research papers

Improved effective thermal conductivity of sand bed in thermal energy storage systems

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ARTICLE INFO

Keywords:
Thermal conductivity
Thermal energy storage materials
Sand
Packed-bed
Cost-effective
Circular economy

ABSTRACT

Thermal energy storage (TES) is becoming increasingly important in the modern energy landscape. As the global energy demand continues to rise and the integration of renewable energy becomes crucial, there is a growing need for sustainable and affordable ways to store energy. TES materials, such as sand, molten salts and heat transfer fluids, are a significant contributing factor to the cost-effective characteristics of TES systems. In recent advancements, sand has been viewed as a high-potential TES material for TES applications, attributed to its thermal resistance, widespread availability, safety, and affordability. However, the low thermal conductivity of sand remains a challenge for some TES applications. This study evaluates different correlations for effective thermal conductivity in a sand-based experimental study where the best correlation was adapted for a numerical simulation of the sand bed. The study further explores the use of discarded metallic chips to enhance the thermal conductivity of the sand. Our experiments assessed two integration techniques using three distinct metallic materials. It was found that the maximum heat rate could be achieved with 20% (volumetric basis) of aluminium chips mixed in sand (1.7 times that of pure sand).

1. Introduction

The urgent need to tackle climate change has spiked significant interest in renewable energy, such as solar and wind. However, these renewable energies are intermittent; thus, the sun and the wind are not always available due to day- and night-time weather conditions [1,2]. Energy storage systems (ESS) are necessary infrastructure to bridge the variable supply of these renewable energies [3]. On account of increasing global energy demand, the usage of ESS is set to increase in utilities and the stabilisation of power grids [4,5]. Advancements in ESS have also made the energy transition agenda into a 100% renewable future feasible [6]. For instance, the development of lithium-ion batteries has become more suitable for e-mobility applications [7,8]. At the same time, other ESS, such as Thermal Energy Storage (TES), can substitute lithium-ion batteries used in stationary electric-grid storage applications to reduce storage costs and wisely utilise limited materials and resources [9].

Among several ESSs, TES systems have emerged as a particularly cost-effective solution [10–12]. Compared to alternatives such as mechanical, electrochemical, electrical or hydrogen storage technologies, TES systems often present a lower upfront capital cost and reduced maintenance costs over their operational lifespan [13,14]. This cost advantage is primarily attributable to using simple, abundant materials such as salts, sand, rocks or phase change materials [15]. Additionally, the scalability of TES systems allows for leveraging economies of scale, further driving down the costs per unit of stored energy. [6] Given the growing demand for flexibility and responsive energy solutions in the renewable-intensive grid, the economic appeal of TES systems is likely to play a pivotal role in shaping the future of the energy landscape.

TES materials intended for sensible heat storage applications can be found in various states, including liquid, molten, and solid phases [16]. Liquid-state TES materials, such as thermal oils and liquid sodium, are frequently employed as heat transfer fluids, benefiting from their exceptional thermal conductivity. In contrast, molten-state TES materials, including molten salts and molten metals, find common use in concentrated solar thermal applications. However, a notable drawback of molten materials is their need to maintain a constant molten state for optimal storage efficiency [17,18]. When these materials cool down, they solidify, potentially causing damage to the storage tank and pipelines. Additionally, specialised metals are required in the construction of...
storage tanks for molten-state TES materials to prevent corrosion, incurring additional costs for the TES system [14,19]. Conversely, solid-state TES materials such as sands have remained relatively underexplored in TES applications. Sands offer the advantage of high thermal tolerance (with a melting point of around 1700 °C), allowing them to substantially enhance Carnot cycle efficiencies due to their wide temperature range [20,21]. Furthermore, sand exhibits a high specific heat capacity, making it well-suited as a TES material for achieving high energy density [22]. Moreover, sand is environmentally friendly and readily available, making it a sustainable choice for TES applications [23].

However, the major drawback of sands in some TES systems is their low thermal conductivity due to their granular form and point contact between the grains of the sand. Thermal conductivity is a fundamental physical property that measures the heat-conducting ability of a material [19]. It describes how well a material can transmit heat, with high thermal conductivity indicating efficient heat transfer and low thermal conductivity signifying poor heat conduction, often resulting in effective thermal insulation. The low thermal conductivity of sand can be a challenging factor for Electro-Thermal Energy Storage systems (ETES) [11] and other TES systems as it has the potential of a low heat transfer rate that can reduce the performance and efficiency of the TES system compared to liquid-state thermal storage materials. There are several publications on the thermal conductivity and thermal properties of sand [24,25]; however, only a few studies have been conducted on improving the thermal conductivity of sand, especially in dry-packed-bed TES systems. Some thermal conductivity improvements of sand have been reported in TES applications, including Chung et al. [26] who proposed a coating of quartz sand to improve solar absorption and thermal stability. Similarly, García-Plaza et al. [27] investigated different sand coatings operating under fluidised bed conditions with a top-concentrated irradiation lamp. In their main findings, coated sand may enhance energy storage efficiency by 60 % to 80 % compared to raw sand. However, the main limitation observed in both studies lies in the preparation process of sand coating, which is unsuitable for large-scale production. Meanwhile, Yi et al. [28] have reported on improving the thermal conductivity of bentonite sand in a ground source heat pump by adding granite powder. Moreover, Babri et al. [29] demonstrated that the heat storage capacity and the thermal conductivity of phase-change materials improved when sand was blended. On a related note, Liu et al. [30] investigated thermal conductivity and predicted a model for mixing sand with recycled rubber tyres. Among many proposed solutions to improving the thermal conductivity of sand, there is still a huge gap in exploring cost-effective solutions, especially for dry sand beds for TES applications.

Apart from altering materials for thermal conductivity improvements, some design choices, such as heating methods, can significantly affect the thermal performance of sand in the packed-bed TES system. Direct solar heating and heating by fluidisation are the most adopted methods in packed-bed-based TES systems [31,32]. Other TES systems adapt the process of circulating heat transfer fluids through heat exchangers in the sand-packed bed [33]. Mixing different heat storage materials to improve the properties of the storage material composite is also possible. However, if the materials themselves are expensive and require mining, then the objective of developing a low-cost and sustainable energy system is in jeopardy.

In contrast, waste material streams often lack direct secondary use and offer a more economical alternative [34]. For instance, at metal workshops, a cut metal “scrap” is created from pure metals but also as mixed metals. Pure metal waste streams could be melted back to pure metals, but this would require the collection of small materials streams and would be impractical [35,36]. Therefore, the possibility of reusing these materials to improve the performance of TES systems would provide a circular economy approach to performance improvements.

In addition to experimental studies, this article also reports a numerical simulation model developed in the COMSOL Multiphysics software. Different correlations for effective thermal conductivity were used, and the results were compared to experimental data. Effective conductivity correlations with and without radiation terms, such as the Yagi-Kuni model [37,38], the Kunii-Smith model [39,40], the Zehner-Schlünder model [39,41], and the Zehner-Bauer-Schlünder (ZBS) model [42], were modelled to represent the experiment results where the best-fit model was adapted for the case study of the experimental setup.

In this study, we propose enhancing the thermal conductivity of sand by incorporating waste metallic chips sourced from machine shops. Leveraging such waste materials for a robust and sustainable ETES [11] system can diminish the cost and energy associated with recycling these discarded alloys while improving the heat transfer efficiency of the Carnot battery. Therefore, in this work, we have approached the improvement of TES from the circular economy angle by utilising scraped metal chips to improve the thermal properties of sand bed. This is a very cost-efficient system to increase the thermal conductivity of the system and has not been previously published. Also, these research findings are transferrable for various applications, including, Carnot batteries, packed-bed energy systems, and underground TES systems.

2. Methods

2.1. Experimental

To investigate the thermal properties of the sand bed, we first constructed a rectangular container made from aluminium, as shown in Fig. 1. The container has a height of 380 mm, length of 230 mm, and width of 380 mm. Two electric heating elements, tubular-type resistance heaters, were fixed in the sand body alongside two thermocouples to log the temperature distribution within the sand bed. The heating elements are 298 mm in height, 309 mm in width, and 50 mm in diameter. These two heaters are positioned in the centre of the box and are 95 mm apart. Each heater is controlled by a 2 kW On/Off control box unit with a temperature regulation range of 1000 °C. K-type thermocouples were used: one is positioned between the two heating elements (45 ±0.7 mm from each heater), and the other is positioned 30 mm away from the heating element. The top of the sand bed was exposed to ambient air (T typically below 26 °C) without insulation.

A combination of sand and metallic by-products, known for superior thermal conductivities, was employed to enhance the effective thermal conductivity of the sand bed in the absence of moisture. In this study, we used Brown Silica sand [43], aluminium, brass and mixed metal chips, as shown in Fig. 2. The detailed properties of the materials are as follows:

**Brown silica** sand is primarily composed of silica (SiO₂) but distinguishes itself with its brownish colour, as seen in Fig. 2A. The grain size of brown silica sand typically ranges between 0.06 and 0.2 mm. Brown silica sand is characterised by a melting point of 1713 °C, a specific heat capacity of 703 J/(kg·K), and a thermal conductivity between 0.2 and 0.7 W/(m·K), with a bulk density of 1800 kg/m³ [44].

**Aluminium chips** were obtained from lathe machining processes and are fragmented aluminium pieces. These chips are 15 to 20 mm long, 0.5 mm in thickness and 1.5 mm in width. Aluminium possesses a melting point of 660 °C, a specific heat of 897 J/(kg·K), and a remarkable thermal conductivity of 205 W/(m·K). Aluminium is very light, with a density of 2712 kg/m³ [45].

**Brass chips**, an alloy primarily consisting of copper and zinc metals, emerge as a by-product of wire EDM machining activities. These chips are usually in wire form with a diameter of 0.25 mm and 4.5 mm long, as seen in Fig. 2C. Their melting temperatures are between 900 °C and 940 °C depending on the brass alloy composition. Brass has a specific heat of around 380 J/(kg·K), a thermal conductivity close to 113 W/(m·K), and its density ranges between 8430 and 8730 kg/m³ [45].

**Mixed metal chips** comprise 90 % steel and 10 % aluminium, often resulting from the lathe and drilling machines' machining processes. These chip sizes are 10 to 15 mm long, 0.5 mm in thickness and 1.5 mm
in breadth. The steel in this blend has a melting point that sits between 1370 °C and 1540 °C, along with a specific heat of 490 J/(kg·K) and a thermal conductivity that ranges from 50 to 70 W/(m·K), depending on the alloy type. The density of steel is around 7850 kg/m³.

Materials with higher thermal conductivity were mixed with the sand to improve the thermal conductivity of the sand bed. Two cases were studied: the layer method and the uniform method, and they are summarized in Table 1. With the layer method, the sand and the metal chips were packed in layers such that the metal chips accounted for 20 % of the total volume of the sand bed as shown in Fig. 1C. The sand sections consist of 8 layers which are separated by 10 ± 1 mm thickness of metal chips layers. A 60 ± 1 mm thickness of sand layer starts at the base of the bed and the remaining 7 layers each measure 30 ± 1 mm. Furthermore, the metal chip layers are each in alignment and in direct contact with the length after each curve of the electric heating element. The mixture is uniformly mixed to represent the uniform method without any changes to the composite. Finally, we also wanted to test how the amount of additive metal chips would impact the thermal properties and a study with varying amounts of aluminium chips in the sand bed was performed.

2.2. Modelling

The modelling process began with a focus on establishing the fundamental geometry. A CAD model of the TES was imported to COMSOL as a starting point. Four points were added to the geometry to represent the location of the four thermocouples used in the experimental setup as shown in Fig. 3. These are later used to evaluate the temperature at these points in the geometry for comparison with the experimental data.

Next, material properties are assigned to the different domains and boundaries of the TES system. The thermal reservoir is contained in an aluminium container, and the reservoir itself is modelled as a solid. This is a simplified representation since the storage material is a porous medium consisting of a matrix of silica sand grains and air-filled void spaces. In order to conserve computational resources, the effective medium technique is used, modelling the porous medium as a homogeneous solid with effective characteristics. The heaters are modelled as uniform heat sources made of solid Incoloy 800. In reality, the heaters consist of an inner core of coiled resistive wire surrounded by a packed magnesium oxide powder with an Incoloy shell. Modelling the intricacies of the heater using the electromagnetic heating module of COMSOL is beyond the scope of this work, and the heating elements are each represented simply as volumetric heat sources. Next, the Heat Transfer in the Solids module is applied to the model.

The equation of heat transfer is given in Eq. (1).

\[ \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \mathbf{q} = Q \]

where:

\[ \mathbf{q} = -k \nabla T \]
The partial differential notation is used in Eq. (1) because the temperature in the TES is a multivariate function of space and time. The thermal conductivity of bulk sand, \(k\), is temperature-dependent and complex to calculate due to the numerous heat transfer pathways between sand grains and void spaces. There are numerous correlations for the effective thermal conductivity of porous mediums such as sand. The Yagi-Kunii [38], Kunii-Smith [50], Zehner-Schlünder [41], Zehner-Bauer-Schlünder [42], Batchelor, Hadley, and Gonzo [40] correlations were tested in this work. These correlations, presented in the Supplementary Materials, incorporate the different heat transfer pathways in the medium, including intra- and interparticle conduction, convection, and radiation. In this way, multiple heat transfer mechanisms are accounted for in a single term: the effective thermal conductivity. The correlations do not consider the effect of bulk fluid movement through the medium; that is, forced convection is not considered here. When possible, the correlations were tested with and without the radiation term to determine the significance of thermal radiation on the effective conductivity.

All domains are given an initial temperature of 12 °C as an initial condition. The bottom surface of the aluminium container is assigned a thermal insulation boundary condition. Surface-to-ambient radiative heat flux is applied to all surfaces in contact with air, governed by the equation:

\[-\mathbf{n} \cdot \mathbf{q} = \psi \sigma (T_{\text{amb}}^4 - T^4)\]  

Fig. 2. Materials used in the sand bed experiment are (A) Brown silica sand, (B) aluminium chips, (C) brass chips and (D) a mixture of metallic chips (mainly steel). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Experiment matrix table indicating blend percentages (volume base) with sand on two mixing methods.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Methods</th>
<th>Layer</th>
<th>Uniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Sand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminium Chips</td>
<td></td>
<td>20 %</td>
<td>20 %, 10 %, 5 %</td>
</tr>
<tr>
<td>Brass Chips</td>
<td></td>
<td>20 %</td>
<td>20 %</td>
</tr>
<tr>
<td>Mix-Metalic Chips</td>
<td></td>
<td>20 %</td>
<td>20 %</td>
</tr>
</tbody>
</table>
where, $\hat{n}$ is a vector normal to the surface, $\psi$ is the surface emissivity of the material, $\sigma$ is a Stefan-Boltzmann constant [W/m² K⁴] and $T_{\text{amb}}$: ambient temperature [K].

Additionally, convective heat flux is applied to these surfaces, with a constant heat transfer coefficient of 5 W/(m²⋅K) to simulate natural convection with air. This process is dictated by the following equation;

$$\hat{n} \cdot \hat{q} = h(T_{\text{amb}} - T)$$  (3)

where $h$ is the heat transfer coefficient [W/m² K].

Finally, both heaters are modelled as conditional heat sources. The heat sources are applied according to an if-statement to represent the On/Off controllers: The heater temperature is measured at the contact point of the thermocouple; if the heater temperature is less than 500 °C, then the heater domain becomes a constant heat source of 2000 W. Otherwise, it is zero watts. The relevant variables used in these equations are defined in Table 2. For the loss terms (surface emissivity and natural convection of air), values are used from the low end of reported literature values. In this way, the model represents a low thermal loss scenario. A high thermal loss scenario is also tested and reported in the Results section to explore the model sensitivity to these parameters.

The mesh is a physics-controlled free-tetrahedral mesh, constrained by the condition that the maximum element size is 0.0579/MRF meters, where MRF is the mesh refinement factor. An MRF of 1 corresponds approximately to COMSOL’s “Coarse” physics-defined mesh size for this geometry and physics module. An MRF of 2 is selected as the “base case,” and a mesh refinement study is performed with MRF = 1, MRF = 2, and MRF = 3, corresponding to increasingly fine meshes as shown in Fig. 4.

### 2.3. Heat rate calculation

To determine the performance of effective thermal conductivity for each composite, we used the heat rate approach, which is defined as the change in temperature increase per unit of time. The following steps were taken for each composite mixture and compared to the pure sand. In the same preamble, the experimental data was collected throughout the heating process, where samples of pure sand and sand mixed with different percentages of aluminium (5 %, 10 %, and 20 % by volume) were subjected to a gradual increase in temperature. The temperature of each sample was taken at 50 °C intervals from an initial temperature of 50 °C to a final temperature of 500 °C. The time in seconds was recorded for each temperature increment, resulting in a set of temperature-time points for each composite.

The heat rate (HR) at each temperature interval was calculated by taking the differential of temperature over the differential of time using the formula:

$$HR = \frac{\Delta T}{\Delta t}$$  (4)

where $\Delta T$ is the temperature change between two consecutive measurements, and $\Delta t$ is the change in time for the same interval.

Once the heat rate for all intervals was computed, the maximum heat rate for each composite was identified and compared to the average heat rate of the pure sand.

### 3. Results and discussion

Sand is a valuable resource used in domestic and commercial applications. Due to its affordability and abundance, the exploits of sand in TES system applications have become a fundamental interest. However, for a Carnot battery system to function effectively without additional...
heat transfer units, the thermal conductivity of the TES material must be compatible with the energy consumption rate of the energy conversion unit. For instance, in our Carnot battery design, we use a Stirling engine, which is embedded directly into the TES material. To utilise sand as the TES material, the thermal conductivity of the sand must be sufficient to meet the heat requirements Stirling Engine. If the thermal conductivity of the TES material is low, it can cause the Stirling engine to cease operating due to a delay in heat transfer. To avoid this issue when using sand, its thermal properties were improved by adding scrap metal chips to the composite.

In this section, we present the findings of computational modelling to better understand heat conduction in the packed sand bed, as well as the experimental values to validate the modelling work and propose improvements for increasing the thermal conductivity of sand.

We first examined the heat transfer in a pure sand bed by recording the temperature profile at specific locations in the sand bed as T3, T4 and Heaters (T1, T2), as shown in Fig. 1A, where the measured temperature profiles for these different thermocouples are presented in Fig. 5.

We can observe from Fig. 5 that the surface temperature of the electric heaters increased to the set temperature (500 °C) within 30 min and maintained a constant temperature for continuous heating. Within the first 75 min, the T4 region heats up faster than the T3 region since the T4 region is 17.5 mm closer to the heat source than the T3 region. However, after 80 min, the T3 region becomes hotter than the T4 region. Eventually, the T3 region becomes equal to the surface temperature of the heaters after 7 h of continuous heating. As heat travels across the sand bed from one side of the heater to the surroundings, we observe a declining temperature gradient, which is why T4 becomes constant at 350 °C after 3 h. Moreover, since there is no insulation around the sandbox, the region outside the heating elements to the surroundings shows a rapid decline in temperature, in contrast to the T3 region between the heating elements. Naturally, unlike the boundary conditions where heat is rapidly lost to the environment without insulation, the T3 region conforms to a different set of boundary conditions.

First and foremost, the T3 region becomes a heat trap or accumulation region since the heat sources on both sides block the pathway for the heat stored to dissipate to the surroundings quickly. Another contributing factor is that the T3 region experiences terminal lag. Since the sand has a low thermal conductivity but high heat capacity, the cooling effect will take longer once heated up, even when the heat sources are temporarily switched off. In this context, we can expect an almost uniform temperature gradient between closely placed heat sources. With this knowledge, we design efficient heating systems for TES systems that utilise packed beds so that the bed attains a uniform temperature distribution without any mixing mechanism involved. In other words, we can increase efficiency by minimising moving parts, lowering costs, and simplifying system design.

To better understand the heat transfer phenomena, we modelled the thermal conductivity of the sand bed using COMSOL Multiphysics. Numerous expressions describe the effective thermal conductivity of granular materials like sand, and these expressions depend on several parameters that were experimentally obtained for the specific sand used in this experiment. These values were fed into the created models, and the corresponding plots are shown in Fig. 6A-B. Fig. 6A considers seven expressions for effective thermal conductivity, which do not include radiation heat transfer within the sand. These include simplified Kunii-Smith and Yangi-Kunii correlations; two simplified Zehner correlations, and Batchelor, Handley and Gonzo correlations. Fig. 6B presents five expressions considering radiation components: the full Kunii-Smith and Yangi-Kunii correlations and the full Zehner-Schlünder and ZBS correlations.

The trends in radiation and non-radiation cases are generally linear since the thermal conductivity for both grain and air increases linearly with increasing temperature. At lower temperatures, thermal radiation among granular materials is almost negligible, and it can be observed when comparing Fig. 6A and B. The correlations that include radiation have a slightly positive curvature due to the influence of thermal radiation between grains; this is because the radiation term, while small, increases with increasing temperature. Moreover, this influence increases at higher temperatures, with larger grain sizes, or with more emissive particles. The ZBS model is a development of the Zehner-Schlünder model that includes a contact area term between the particles, showing that the inclusion of this term has a negligible effect on the predicted effective thermal conductivity since the ZBS curve rests only slightly higher than the Zehner-Schlünder curve on both graphs. This implies that the contact area may have negligible heat transfer effects for the sand of this grain size.

Each of these correlations represents predictive models for the thermal conductivity of sand and are derived by the referenced authors based on theoretical principles of heat transfer. Many include experimental fitting parameters, as shown in the tables presented in the Supplementary Materials. Because the thermal conductivity of sand was not experimentally measured in this work, the accuracy of these correlations is not directly verified; instead, their suitability is determined based on how well they contribute to the overall heat transfer model, developed in COMSOL.

To simulate the charging of the sandbox, the values for effective thermal conductivity for the correlations were fed to the COMSOL model, along with the necessary parameters. The Zehner-Schlünder correlation results were not passed to the COMSOL model, since they predicted nearly the same conductivities as the ZBS correlations. The COMSOL model gives the temperature at all points and at all times throughout the sandbox. The temperature at points T1, T2, T3 and T4 are evaluated and compared to the experimental results. Fig. 6A presents the comparison at the middle thermocouple (T3). Fig. 6B presents the average root-mean-squared error (RMSE) method, shown here.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (T_{\text{mod},i} - T_{\text{msd},i})^2}$$

Fifty-one time steps were used in the error calculation, from $t = 0$ to $t = 5$ h, with increments of 0.1 h. The ZBS correlation, which includes a
radiation term, resulted in the lowest RMSE for all three thermocouple locations. This indicates that, of the correlations considered, the ZBS with radiation correlation produced the most accurate prediction for the effective thermal conductivity of the sand.

From Fig. 7A, it becomes clear that the correlations which predicted a higher thermal conductivity resulted in a higher temperature in the region between the heaters (T3). This is because heat is more easily conducted through the materials with higher thermal conductivities, which also holds for the region outside the heaters, T4. The correlations that yielded the most accurate temperature predictions at each point were the correlations with the highest conductivities: the Hadley and Gonzo correlations and the Zehner-Bauer correlation, including the radiation term. Measurements of the sand thermal conductivity via the modified transient plane source technique showed the sand conductivity at room temperature to be approximately 0.114 W/(m·K). This implies that the Yagi-Kunii and Kunii-Smith correlations may better approximate the effective thermal conductivity at low temperatures, while the Hadley, Gonzo, and Zehner models better approximate it across the...
entire temperature range. Thus, an effective thermal conductivity correlation with a steeper slope and more temperature dependence may be more accurate. The ZBS + Radiation correlation for conductivity resulted in the most accurate temperature prediction by the COMSOL model, showing an average error below 8 °C, as seen in Fig. 7B. Since the ZBS with Radiation term correlation is the most accurate for this system, we plot it again with the measured values for each temperature location shown in Fig. 8.

Fig. 8 shows a close match between the modelled and the measured data for the surface temperature of the heaters (T1, T2) and the region outside the heaters T4. This shows the model works well with solid materials across the studied temperature range. Again, the Zehner-Bauer with Radiation term correlation proves the model works well with granular materials like sand at temperatures below 350 °C. Higher temperatures result in higher radiation, significantly affecting effective thermal conductivity. Another factor to consider is that having two heat sources in parallel has not been studied to accurately predict the effective thermal conductivity of granular materials occurring between the region of the heat sources. The curve T3 modelling shows that the modelled results deviate slightly from the measured data at temperatures above 350 °C in this region. The temperature distribution throughout the sand bed is a result of a complex interaction between the heat source terms, loss terms, and heat transfer rates. It may be the case that the heaters are oversimplified and that the physical heaters are nonuniform heat sources. A more precise understanding of the heater power delivery, as well as the heat loss rates at the edges of the TES, could further improve the model.

3.1. Mesh and thermal loss sensitivity

A mesh refinement study with MRF = 1, 2 and 3 showed adequate convergence, and refinement factors of 2 and 3 produced nearly identical model results. Running the simulation with MRF = 2 took just under two hours, while MRF = 3 took 3.5 h; therefore, MRF = 2 is considered adequate and time-efficient for this study.

The sand and aluminium surface emissivity, as well as the coefficient of heat transfer for natural convection, dictate the thermal losses at the edge of the modelled system. To explore the model sensitivity to these terms, they were increased to the higher end of literature reported values and applied to the model, along with the ZBS with radiation correlation for thermal conductivity. The original values are presented in Table 2, while the increased values are as follows: $\psi_f = 0.97$, $\psi_{dum} = 0.3$, $\Psi_{air} = 20\text{ W/(m}^2\cdot\text{K)}$, and the simulated charging time was five hours. This 8 % increase in sand emissivity, a threefold increase in aluminium emissivity, and a fourfold increase in convection coefficient resulted in a 1 % decrease in the average temperature at the midpoint (T3), and a 6 % decrease in the average temperature at the outside point (T4). The model therefore demonstrates relatively low sensitivity to these loss terms.

3.2. Improving the heat transfer in the sand bed

In order to improve the thermal conductivity of the sand bed at a relatively low additional cost, different waste metal chips were mixed with sand. Three different metallic chips, aluminium, brass and mixed metals (mainly steel) were studied. The following experiments were performed with a homogeneous mixture of the metallic chips and the sand (chip: sand ratio of 7.26 by volume), while the portion of sand and chips remains the same as in the layer composite cases. Fig. 9A and B show the temperature profile of the two thermocouples for the different layering methods (Layer and Uniform) for all metal-sand mixtures, and Table 3 summarises the heat rates and the performance of the composites (relative to sand) calculated from these experiments.

Fig. 9A and B show that the thermal conductivity in the two arrangements differs; however, they have the same composition sand, Therefore, may differ in costs. Focusing on the temperature profiles between the heating elements T3 shown in Fig. 9A, we can observe that the mixtures have different thermal conductivities according to the time each curve reaches 500 °C. Notably, the brass-sand layer demonstrates the highest effective thermal conductivity, which can be observed from the maximum heat rate value at 8.8 °C/min, marking a remarkable 1.79 times the value of pure sand at 5 °C/min. Subsequently, the mix-metal chips layers exhibit the next highest performance of 1.76 times, followed by the aluminium-sand layers at 1.71 times. Among the uniform composites, aluminium-sand uniform shows the highest maximum heat rate, which is 1.70 times that of pure sand, followed by brass-sand uniform at 1.65 times and mix-metal-sand uniform at 1.48 times, representing the lowest composite value.

The physical properties of the metal chips have a significant impact on the thermal properties of the sand bed. For instance, the thermal conductivity of aluminium is almost twice as high as brass; however, the brass-sand layer arrangement is more effective than the others. The main reason for this occurrence is that brass has at least three times higher density than aluminium. Moreover, the brass chips used for this experiment are less porous and compact since they are the waste chips from the EDM brass wire cutter machine. Unlike the aluminium and the mixed metal chips produced by the lathe machine, which have irregular shapes in string and flake form, the brass chips are straight pieces of wire. This makes the layer case accommodate more brass chip material and eliminates porous spaces due to its shape and size, making the brass chip layers behave as heat-conducting fins in the sand bed. Moreover, in the uniform mixture case, the aluminium chips are more effective than the brass and mix-metal chips simply due to the high thermal conductivity of aluminium. On the other hand, mix-metal appears to have a low performance since 90 % is steel, which has a lower thermal conductivity than aluminium and brass.

Fig. 9B shows the temperature increase outside the thermocouples with the different material compositions. We can observe that higher temperature levels can be obtained with the metal composite cases compared to the pure sand case. Even though sand has an extremely high-temperature tolerance, it also has a high thermal resistance, making it challenging to transfer heat energy effectively, especially from a resistance heater in a large sand bed. However, metallic chips in the sand create a pathway for heat to travel easily across the sand bed and utilise more storage space. This enables TES systems, such as Carnot batteries to significantly enhance their efficiency since there will be less thermal resistance when charging and discharging the storage. Among all the cases, the aluminium-sand uniform case has shown to be the most economically viable solution, making it the most favourable option for
Finding the optimal quantity of metal chips with the lowest additional cost would be vital for the lowest impact on the system cost. Table 4 presents the cost associated to the scrap metals used in this study.

As the aluminium uniform case showed the most significant improvement after brass, and the price of aluminium scrap metals is four times cheaper than brass scraps [50], it is reasonable to choose aluminium for the sensitivity analysis with respect to the composition. Three compositions were tested: 5 %, 10 % and 20 % volume of aluminium chips in sand, and the results are presented in Fig. 10A, B, and Table 5.

Fig. 10A shows that the higher the aluminium chip content in sand, the higher the thermal conductivity. For a 20 % aluminium chip content, the maximum heat rate is 8.4 °C/min, which is 1.7 times pure sand’s maximum heat rate, as shown in Table 5. In comparison, 10 % and 5 % aluminium chip content yield maximum heat that are 1.36 times and 1.18 times of pure sand, respectively. The reason can be that the more aluminium chips in the sand bed, the higher the percolation, leading to higher thermal conductivity. Since the chip concentration is enough in the sand bed, more interconnections among the chips make heat transfer easy. When the percolation is below or just near the percolation threshold, the chips become isolated from each other in the mixture due to low concentration, creating fewer conductive paths and causing low thermal conductivity.

Similarly, in Fig. 10B, we can observe that 20 % of the aluminium chip composite increases the stable T4 temperature, while we see almost no visible changes with the 10 % and 5 % aluminium chip composites. This also implies that more chips in the sand increase the overall temperature gradient profile of the sand bed. Therefore, a 20 % aluminium chip content of a TES pack bed shows higher effective thermal conductivity compared to the 5 %, 10 % aluminium chip content and pure sand.

<table>
<thead>
<tr>
<th>Scrap metals</th>
<th>Commercial scrap metal prices in Finland [50]</th>
<th>Commercial price of scrap metals in Finland including aluminium, brass and stainless steel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>0.7</td>
<td>Price €/kg</td>
</tr>
<tr>
<td>Brass</td>
<td>3.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>0.75</td>
<td>0.75</td>
</tr>
</tbody>
</table>
sand. For instance, a Carnot battery system that utilises Stirling Engines to convert stored heat in the packed bed to produce electricity will use most of the stored heat due to the higher thermal conduction effect.

3.3. Comparison of other studies with the conducted research

In this paper, a comparative analysis to illustrate the significant advancements and the distinctive contributions of our research in enhancing the effective thermal conductivity of sand beds for thermal energy storage (TES) applications was conducted. This comparison, summarized in Table 6, positions our study within the context of efforts to improve the thermal performance of materials used in TES systems.

Our investigation reveals that previous studies mainly target CSP systems and underground TES systems. Methods involving the coating of sand particles [26,27] are often focused on enhancing solar thermal absorption, while the remaining studies involve mixing materials with sand particles [28–30]. Compared to the methods presented in [28–30], our studies tolerate wide temperature range operation while others are limited to low-temperature operation, frequently in conjunction with heat pumps. In contrast, our study not only suits Carnot batteries but also shows promise for underground TES systems. This could potentially remove the need for heat pumps, offering a cost-effective alternative for TES applications.

4. Conclusion

Our study highlights the importance of increasing the thermal conductivity in solids-based TES systems to ensure efficient heat inset and

<table>
<thead>
<tr>
<th>References</th>
<th>Focus</th>
<th>Material(s) Tested</th>
<th>Applications</th>
<th>Methodology</th>
<th>Tested Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chung et al. [26]</td>
<td>Coating sand particles to increase thermal absorptivity for CSP</td>
<td>Quartz sand coated with silica shell containing black spinel nanoparticles.</td>
<td>CSP systems as HTF and TES material.</td>
<td>Coating process to absorptance solar thermal properties.</td>
<td>20 °C to 700 °C</td>
</tr>
<tr>
<td>García-Plaza et al. [27]</td>
<td>Coating sand particles to increase thermal absorptivity for CSP.</td>
<td>Sand coated with graphite and carbon black.</td>
<td>CSP systems, TES materials in fluidized beds.</td>
<td>Lab-scale fluidized bed testing with concentrated irradiation.</td>
<td>20 °C to 210 °C</td>
</tr>
<tr>
<td>Yi et al. [28]</td>
<td>Effect of granite powder on thermal conductivity for ground-source heat pumps.</td>
<td>Granite powder added to bentonite-based source heat pump backfill.</td>
<td>TES material for Ground-source heat pump system.</td>
<td>Analysis of varying granite powder content, dry density, and water content.</td>
<td>NA</td>
</tr>
<tr>
<td>Barbi et al. [29]</td>
<td>Evaluating PCMs mixed with sand for LHTES in shallow geothermal applications.</td>
<td>N-Octadecane and commercial paraffin-based PCM mixed with sand.</td>
<td>TES material for Ground-source heat pump system.</td>
<td>Thermal cycle testing, grain size laser diffraction, ESEM-EDS, and FTIR analysis.</td>
<td>12 °C to 35 °C</td>
</tr>
<tr>
<td>This Study</td>
<td>Improving thermal conductivity of sand bed by integrating metal chips.</td>
<td>Sand mixed with scrap metal chips.</td>
<td>Carnot Batteries and TES systems with packed beds.</td>
<td>Experimental study and numerical simulation by mixing sand with metal chips.</td>
<td>20 °C to 500 °C</td>
</tr>
</tbody>
</table>

Fig. 10. Comparison of different compositions of aluminium chip content: 5%, 10% and 20% uniformly mixed with sand. The vertical axis shows temperature readings from thermocouples T3 (A) and T4 (B).
heat recovery from storage. Sand is an attractive heat storage material for packed bed TES systems because of its low cost and abundance. However, its naturally low thermal conductivity presents challenges for the thermal management of the system. We conducted computer simulations and experimental work to understand heat transfer in sand and find ways to improve its thermal performance. Using COMSOL Multiphysics, we compared thermal conductivity models explicitly designed for granular materials like sand. The ZBS model, which includes a radiation component, corresponds well with the experimental values of a sand bed; however, there is a 5% mismatch with the experiment results at high temperatures. This finding emphasizes the complexity of heat transfer in such materials and highlights the need to consider radiative effects.

To further improve the thermal properties of sand beds, we studied the addition of metallic chips to the sand with low additional cost. Layers of brass and sand showed the best improvement in thermal conductivity. Mixtures of sand and aluminium chips gave a balanced thermal performance. These mixtures help overcome the natural limitations of sand and increase the overall thermal performance of the packed bed. We also studied how the amount of metallic chips affected the thermal properties. The conductivity and capacity improved as we increased the amount of aluminium chips. Interestingly, a mixture with 20% aluminium provided a vast margin of effective thermal conductivity in comparison to 5%, 10% aluminium in sand and pure sand.

In conclusion, sand has potential for TES systems, but its natural thermal limitations require creative solutions. Adding metallic chips is a promising approach to improve conductivity and storage capacity. With the increasing global focus on sustainable energy, this research is timely and essential, pointing to new energy storage methods.

While the focus of this study has discovered the phenomena in thermal energy storage systems applications that have packed bed systems, we continue to develop the model for entirely Electro-Thermal Energy storage system (ETES). Additionally, we are constructing a large scale experimental ETES system where several different storage material performances can be tested.

CRediT authorship contribution statement

Sampson Tetteh: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Gabriel Juul: Writing – original draft, Methodology, Data curation, Conceptualization.

Mika Järvinen: Writing – review & editing, Validation, Supervision, Conceptualization.

Annukka Santasalo-Aarnio: Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly to improve language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

The research received funding from The Finnish Cultural Foundation Suomen Kulttuuri Rahasto (49415F2A), Tekniikan Edistämisäätiö (9080) and the Research Council of Finland funding through Grant 326346 for profiling funding.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.est.2024.111350.

References


