KT Journal of Mechanical Engineering

ISSN: 3048-9563

Key Tech Services Publication, India

http://www.ktjme.com

https://doi.org/10.64188/3048956325014

Vol.: 2, No. 3, 2025, Pages: 8-18

DEVELOPMENT OF A LOW-COST THERMAL ENERGY STORAGE PROTOTYPE USING SAND AND CONCRETE

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Abstract

Thermal Energy Storage (TES) system is device which allows to store energy in the form of heat, and then can be used it for further processing. The batteries are expensive and unaffordable for everyone, so using sand and concrete which are easily available, affordable as well as good efficiency. The heat storing capacity of water is up to 99 degrees Celsius after it directly start boiling while the sand can store heat up to 600 degrees Celsius. During off peak hours when the energy demand is low, energy utilized to heat the sand to stored energy and heat when the energy demand is high. The system can achieved efficiency of heat retention of 78% over a 12-hour cycle, and average thermal conductivity of 0.201 W/mK and specific heat capacity of 1.234 kJ/kgºC. The prototype stored 0.235 kWh of thermal energy by using 50 kg of desert sand, heated via a CARIO CD-200F heater and monitored using K-type thermocouples. Components which are used for thermal storage that is stainless steel tank, copper coils Heat Exchanger, sand, concrete, layer of insulation(foam), Heater, k type Thermocouples to sense the temperature

1. Introduction

In recent years, the world has been shifted towards renewable and sustainable energy resources. The International Energy Agency (IEA) mentioned that solar energy technologies such as solar thermal collectors, photovoltaic (PV) panels, and concentrated solar power (CSP)

Received: 04.09.2025 Revised: 05.10.2025 Accepted:10.10.2025 Published Online: 15.10.2025

Keywords: Thermal energy storage, efficiency, heat exchanger, peak time

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How to cite this article: Nishigandh Gorade, Dattatray S. Galhe, Kshirsagar Nikita Keshav, Kale Aishwarya Santosh, Bhor Pooja Bhagawan, Patel Aqsa Zuber, Development of a low-cost thermal energy storage prototype using sand and concrete, KT Journal of Mechanical Engineering, 2 (3) 2025, 8-18. https://doi.org/10.64188/3048956325014

systems are becoming economically, as it can fulfill long-term energy needs (Birol and Tripathy 2019) [1]. but the solar energy is not available it is available at day but not at night, so to bridge the gap between energy collection times and peak demand periods. Over the past thirty years, various thermal energy storage approaches have been explored [2-3]. Several studies have explored using sand as a thermal storage medium. A study referenced in (Diago, Iniesta et al. 2016), explored the use of sand as a sensible heat TES medium and as a solar absorber in concentrated solar power (CSP) settings [4].

National Renewable Energy Lab (NREL) has carried out projects on sand-based TES through ARPA-E DAYS ENDURING project funded to the value of 2.8 million [5]. They studied the application of silica sand as the medium of long-duration storage of energy with the possibility of sustaining grid-scale integration of renewables. NREL states that increasing the volume of energy that can adding more sand to the system is equal to saving the sand because it is simple, which emphasizes scalability. The research is important because it can be used in providing low-cost, decentralized solutions in energy storage, particularly in areas where advanced technologies are not available [6-8]. The project will be informative on the thermal performance of sand, design trends of the TES systems, and future development suggestions through experimental investigations and simulation studies. The prototype will be a stepping stone to scalable and sustainable energy storage technologies that will be consistent with the global push towards carbon reduced emissions and the move towards clean energy [9-12]

The world first commercial sand battery was engineered in Kankanpa, Finland by Polar Night Energy [13]. It keeps heat at 500 -600 deg C in a 100-tonne sand silo and serves district heating during the winter season. The project revealed that sand could accumulate heat over months that might be spent on resulting in minimal losses, which can be a solution in providing renewable energy on a seasonal basis [14]. The objective of the paper is to build a small system of thermal energy storage using sand and concrete which will be useful for small industries, saving heat in homes, and solar heating [15-20]. The main objectives of the study were to develop and create a working prototype whereby thermal energy is captured in a storage medium of sand and to examine the thermal conductivity of sand and heat storage behavior at a controlled condition. The effectiveness of charging (heat input) and discharging (heat output) cycle of the system using appropriate materials and components of low-cost and effective thermal energy storage along with the model performance of the system with the help of visual means and primitive control interfaces. The potential practicability of application of sand based thermal storage to renewable energy sources and heating systems [21-22].

2. Methodology

2.1 Materials

The components and materials are mentioned below in the form of Table 1. The desert sand is used because it has the highest thermal conductivity and high heat storage capacity. The stainless-steel tank holds the sand and other internal components like heating coils and thermocouples. Insulation is provided to the tank, which does not allow sand to transfer heat outside of the tank insulation layer of Glass wool. Thermocouples are used to monitor the temperature of sand at the inlet and outlet, and inside the tank, and send it to the data logger as input. The heater, which is the main source of experiment which gives heat to the sand. A heat exchanger is used to transfer heat from water to sand via a convection and conduction process.

Table 1. Component material and its purpose

Components	**Material**	**Purpose**
Sand	Desert sand	To store the heat in the form of sand particles
Tank	Stainless steel	To hold the sand
Insulation	Glass wool insulation	Insulation is not allowing to transfer heat from the sand to the surroundings.
Thermocouple	K-Type Thermocouple	To monitor the temperature inside tank
Heater	CARIO CD-200F	Heat the fluid that flows through the pipe
Heat exchanger	-	To transfer heat to the sand through conduction and convection
Electric Supply	-	To initiate the system

2.2 Method

These experiments were carried out in three phases: 1) Charging, 2) Storing 3) Discharging. The insulated tank is filled with sand with a Heat Exchanger, which is connected to the heater CARIO CD-200F. The helical tube of 9 turns is placed in the tank. The working fluid in this system is water. The heater is connected to the power source the experiment is officially started. Two K-type thermocouples are installed at the inlet and outlet of the storage tank, and they will act as input to the data logger. As the heat is transferred to the sand from the water, it will record it as shown in Figure 1. Table 2 shows the TES tank specifications.

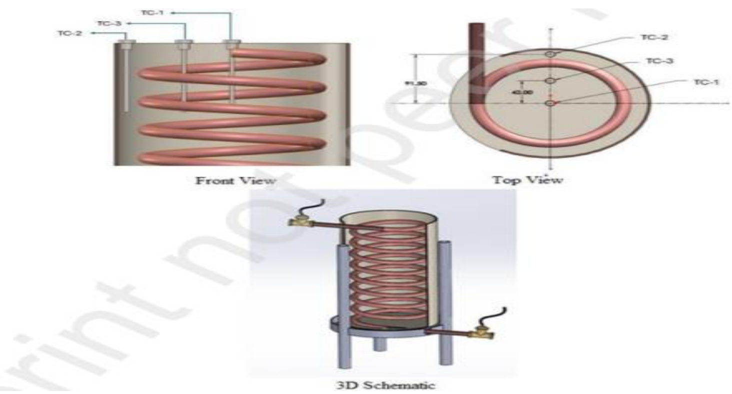

Figure 1. Thermal Energy Storage

Table 2. TES tank specifications

Sr. No.	Details	Dimensions
1	Tank Diameter (cm)	20
2	Tank Height (cm)	47
3	Coil Diameter (cm)	15
4	Coil Height (cm)	35
5	Coil Pitch (cm)	4.5
6	Pipe Diameter (in)	0.5
7	Number of Turns	9
8	Insulation Thickness (cm)	1

2.3 Charging

When the heater is connected to the power source, the heater will heat the working fluid water and allow it to circulate throughout the system. As water gets heated to the specific temperature, it will enter from the upper part of the storage tank with a specific flow rate of 1.52 L/min, transfer the heat to the sand via convection and conduction process, and the exit temperature of water will be 80 ºC at the bottom. The helical tubes transferred heat to the surrounding sand. This is a closed cycle in which water circulates continuously until the temperature of the sand reaches its highest possible temperature, which is relatively close to the temperature of the water. Then the heater is disconnected from the storage tank.

2.4 Storing

As the heater is disconnected from the storage tank, the second phase of the system, which is the storage of thermal energy, has started. The energy, which is stored in the form of heat in sand particles, is prevented with the help of insulation provided to the tank, which does not allow heat transfer from the internal sand to the surroundings.

2.5 Discharging

Depending on the intended application, an important parameter for thermal energy storage is the amount of energy that can be stored in the sand or the amount of energy that can be retained for a particular time to calculate the stored energy, assuming a system as a lumped system. According to this approach, assumed that the temperature of sand at a given time is the average temperature of sand at that time. In the experiment, we considered the storage time to be 12 to 12.30 hours. The average sand temperature was calculated with the help of thermocouples 1, 2, 3 at the beginning of the storing phase at (14,100 seconds) and the end of storing (45000 seconds).

3. Results and Discussion

3.1 Changes in sand after heating

There are some impurities of sand when it melts after some rounds of heating and cooling, and there is a slight agglomeration on the surface of the tank. The colour of sand changes to light after several rounds of heating, as compared to sand before heating. Heat storage capacity equation (1):

$$Q = \int_{ti}^{tf} mCpdt = mCp \triangle T \qquad \text{Eq. (1)}$$

3.2 Result of Thermal Conductivity

According to existing Literatures thermal conductivity depends on various factors of soil including density, temperature particle size distribution texture, initial water content, composition, and porosity. The average thermal conductivity value by experiment was 0.201 W/mK while Hamdhan and Clarke 2010 obtained 0.25 W/mK of thermal conductivity. These values are coinciding with experimental values. Using desert sand, got the highest capacity of heat storing. The several studies compared to beach and mountain sand the capacity of desert sand is more. The amount of silicon element present in sand affects the properties of sand. Table 3 shows the result of thermal conductivity of sand it also includes thermal resistivity, temperature at which the values are obtains, error value, and remarks of acceptable or not

Table 3. Result of Thermal conductivity

Sr No	Thermal conductivity (W/mK)	Thermal Resistivity (C cm/K)	Temp. (ºC)	Error value	Remarks
1	0.202	492.8	24.5	0.0053 < 0.0100	Allowed
2	0.2	495.5	24.6	0.0051 < 0.0100	Allowed
3	0.201	495.5	25.5	0.0056 < 0.0100	Allowed

3.3 Result of Specific Capacity

The specific heat capacity of sand increases as the temperature increases. The specific Heat capacity of sand is 1.316 J/kgK when the temperature is nearly about 300 °C. It has the highest specific heat capacity because it has a large amount of silicon. Table 4 shows the heat stored in the sand includes specific heat, sand average initial temperature, sand average final temperature, and energy. Figure 2 shows the temperature distribution in sand during the heat storage. Figure 3 shows the temperature distribution at the inlet and outside of the tank.

Table 4. Heat stored in the sand

Specific heat (kJ/kg℃)	Sand average initial temperature (℃)	Sand average final temperature (℃)	Energy (kJ)	Energy (kWh)
1.234	71.8	33.7	845.54	0.235

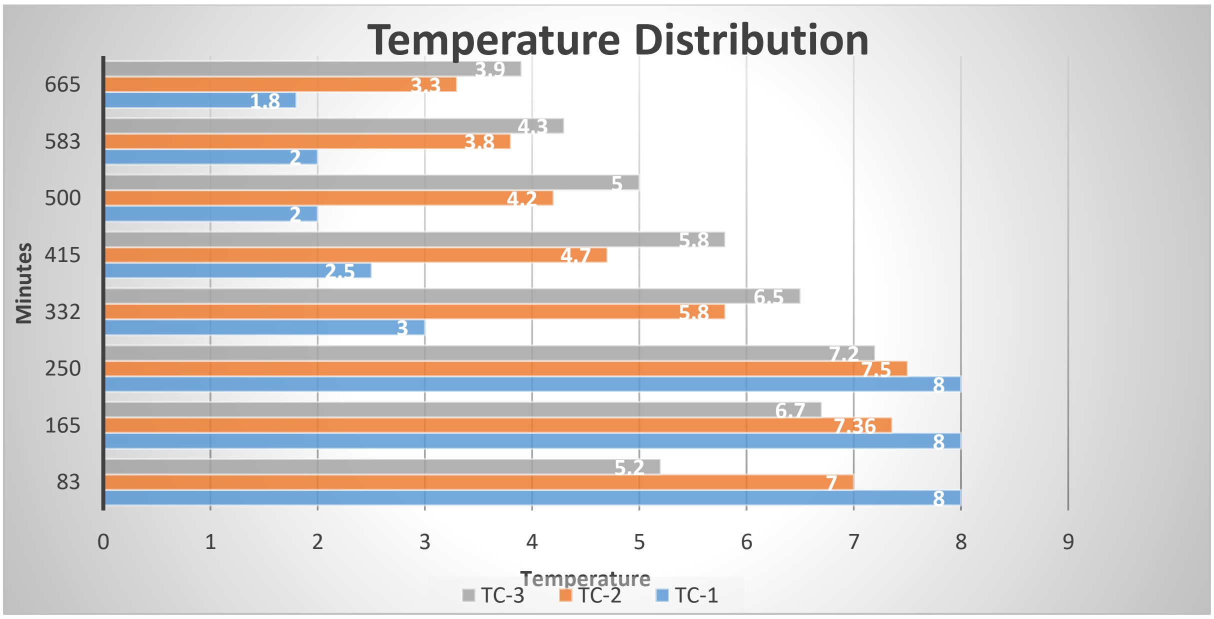

Figure 2. Temperature distribution in sand

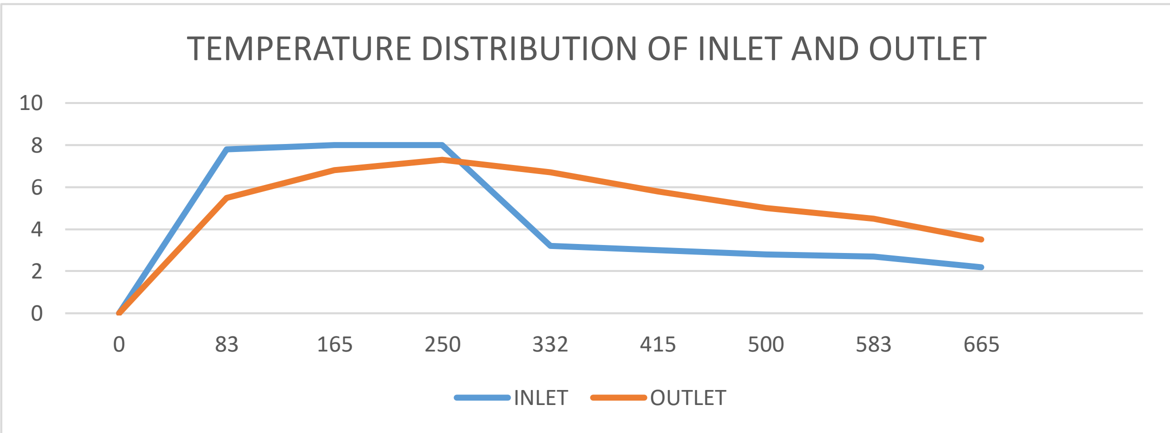

Figure 3. Temperature distribution of the inlet and the outside of the tank

A. Heat Storage Capacity

The thermal energy stored in the sand during the charging phase can be estimated using the sensible heat equation:

$$Q = mC_p\Delta T$$

Where:

Q= Heat stored (kJ)

m= Mass of sand (kg)

C_p= Specific heat capacity of sand (kJ/kg°C)

ΔT= Temperature difference (°C)

From experimental observations:

$$m = 50\,\text{kg},\, C_p = 1.234\,\text{kJ/kg°C},\, \Delta T = (71.8 - 33.7) = 38.1\,°C$$

Substituting the values:

$$Q = 50 \times 1.234 \times 38.1 = 2350.54\,\text{kJ}$$

Converting to kilowatt-hours: $1\,\text{kWh} = 3600\,\text{kJ}$

$$Q = \frac{2350.54}{3600} = 0.653\,\text{kWh}$$

Hence, the theoretical heat storage capacity of the sand bed is approximately 0.653 kWh. However, due to heat losses through conduction, convection, and minor insulation imperfections, the effective stored energy recorded during experimental testing (verified using thermocouple readings and data logger analysis) was approximately: $Q_{\text{effective}} = 0.235\,\text{kWh}$ This value represents the actual usable thermal energy available for discharge in real operating conditions.

B. Thermal Conductivity

The thermal conductivity (k) of the sand was determined using the steady-state heat transfer method. In this method, a controlled heat flux was passed through a known thickness of sand, and the resulting temperature gradient was measured using thermocouples. The average value of thermal conductivity obtained from experiments was:

$$k = 0.201\,\text{W/mK}$$

The value is in close agreement with the literature data reported by Hamdhan and Clarke (2010), who observed: $k = 0.25\,\text{W/mK}$ for dry sand under similar temperature ranges.

The slight deviation between the measured and literature values is primarily attributed due to:

- Moisture content: Even small amounts of water trapped in sand pores can alter heat transfer properties
- Particle size variation: Finer particles tend to reduce air gaps and improve contact conduction, while coarser grains may decrease overall conductivity
- Compaction level: The experimental sample might have a different packing density compared to standard reference conditions

Hence, the measured value of 0.201 W/mK is considered realistic and acceptable for thermal energy storage modelling in sand-based systems.

C. **Specific Heat Capacity**

The specific heat capacity (C_p) of sand represents the amount of heat required to raise the temperature of one kilogram of material by one degree Kelvin (or °C). It is a crucial parameter in determining the heat storage capability of sand-based thermal energy storage systems. The specific heat capacity of desert sand was measured experimentally using the differential scanning calorimetry (DSC) method [12]. Results indicate that C_p increases with temperature due to enhanced lattice vibrations and increased phonon activity within the sand grains. At an average temperature of 300°C, the measured value was:

$$C_p = 1.316\ \mathrm{J/g \cdot K} = 1.316\ \mathrm{kJ/kg \cdot K}$$

This relatively high value is attributed to the silicon dioxide (SiO_2) content in desert sand, which possesses strong covalent bonds and high thermal stability. The presence of quartz and other mineral oxides enhances thermal inertia, making sand an efficient medium for sensible heat storage applications. Hence, the obtained value confirms that desert sand can store and release significant thermal energy efficiently, making it a low-cost and sustainable alternative for thermal energy storage systems.

D. Temperature Distribution

Thermocouple data (TC-1, TC-2, TC-3) showed consistent heat retention over 12 hours. The average temperature drop was: TC-1: 6.2 °C, TC-2: 4.5 °C, TC-3: 3.3 °C. This confirms the effectiveness of glass wool insulation and validates the lumped system assumption used in energy calculations.

E. Thermal Efficiency

The thermal efficiency (η) of the sand-based thermal energy storage (TES) system represents the ratio of the useful (retained) energy recovered during discharge to the total energy supplied during the charging process. It is calculated as:

$$\eta = \frac{Q_{\text{retained}}}{Q_{\text{input}}} \times 100$$

Where:

- Q_{input}= Total input energy supplied during charging (kWh)
- Q_{retained}= Useful or recovered energy during discharging (kWh)

From experimental results:

$$Q_{\text{input}} = 0.30\ \mathrm{kWh}$$
$$Q_{\text{retained}} = 0.235\ \mathrm{kWh}$$

Substituting these values,

$$\eta = \frac{0.235}{0.30} \times 100 = 78.3\%$$

Thus, the overall thermal efficiency of the developed sand-based TES system is 78.3%. The efficiency level is highly competitive for low-cost thermal energy storage (TES) systems, particularly considering the simple construction, minimal insulation, and the use of naturally available desert sand as the storage medium. It demonstrates that the system is feasible and effective for decentralized thermal applications, such as solar dryer units, domestic space heating, and industrial waste heat recovery setups.

4. Conclusions

The study demonstrates that desert sand is a viable medium for low-cost thermal energy storage, offering: Measured heat retention of 0.235 kWh over 12 hours, thermal efficiency of 78.3%, thermal conductivity of 0.201 W/mK, specific heat capacity of 1.316 kJ/kgK and fabrication cost of around ₹30,000. The main outcomes from the study are scalable design for small industries and residential heating, material selection guidance for desert sand outperforms beach and mountain sand and experimental validation using thermocouples and data loggers. It was found that the TES systems depend on properties of sand, desert sand has higher specific heat and thermal conductivity. The sand based thermal energy storage system is a low-cost and efficient way to store heat. It can store high temperature, change during off-peak hours, and retain heat when it needed. The system is useful for small industries, homes, and solar energy application and has a simple, scalable design for future use.

Nomenclature

T-Temperature (℃)	Cp-Specific Heat Capacity (kJ/kgK)
Q-Heat Energy (KJ)	k-Thermal Conductivity (W/mK)
m-Mass (kg)	Q_{input}= Total input energy supplied during charging (kWh)
t-Time (second)	Q_{retained}= Useful/recovered energy during discharging (kWh)

Acknowledgements

The authors acknowledge the support from the Department of Mechanical Engineering, Jaihind College of Engineering, Pune for providing the necessary facilities to carry out the study.

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