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Thermal Behavior and Efficiency Assessment of Packed Bed Sensible Heat Storage Systems

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Abstract- Thermal Energy Storage (TES) systems play a crucial role in enhancing the efficiency, reliability, and sustainability of energy systems by mitigating the mismatch between energy supply and demand. Among various TES technologies, Packed Bed Thermal Energy Storage (PBTES) systems have gained significant attention due to their structural simplicity, low cost, mechanical robustness, and ability to operate over a wide range of temperatures. This study presents a comprehensive experimental investigation of the thermal performance of a packed bed thermal energy storage system using solid filler materials and air as the heat transfer fluid (HTF). The primary objective is to analyze the charging and discharging behavior, temperature stratification, heat transfer effectiveness, and overall thermal efficiency of the system under varying operating conditions.

Keywords: ***Packed bed thermal energy storage, Experimental analysis, Heat transfer, Thermal efficiency, Temperature stratification, Sustainable energy etc.***

1. INTRODUCTION

The increasing global demand for energy, coupled with the urgent need to reduce greenhouse gas emissions, has accelerated the development and deployment of renewable and sustainable energy technologies. However, a fundamental challenge associated with renewable energy sources such as solar and wind is their inherent intermittency and variability. Thermal Energy Storage (TES) systems have emerged as an effective solution to address this issue by storing excess thermal energy during periods of surplus generation and releasing it during periods of high demand. By decoupling energy generation from energy consumption, TES systems significantly enhance the flexibility, efficiency, and reliability of energy systems.

Thermal energy storage technologies can be broadly classified into sensible heat storage, latent heat storage, and thermochemical storage. Among these, sensible heat storage systems are the most widely used due to their simplicity, material availability, and ease of implementation. In sensible heat storage, energy is stored by raising the temperature of a storage medium without undergoing a phase change. Common sensible heat storage systems include water tanks, molten salt systems, concrete storage units, and packed bed thermal energy storage systems.

Packed bed thermal energy storage systems utilize solid storage materials such as rocks, ceramic balls, bricks, or encapsulated phase change materials arranged in a packed configuration within an insulated container. A heat transfer fluid, typically air or oil, flows through the void spaces between the particles, exchanging heat with the solid medium. The large surface area available for heat transfer, combined with the low cost and durability of solid filler materials, makes packed bed systems particularly attractive for medium- and high-temperature applications.

The operational principle of a packed bed TES system involves two main modes: charging and discharging. During the charging process, hot fluid enters the packed bed and transfers heat to the solid particles, gradually raising their temperature. During discharging, cooler fluid is passed through the bed, absorbing the stored heat from the solid medium and exiting at a higher temperature. The thermal performance of the system is governed by several parameters, including particle size, bed porosity, fluid mass flow rate, inlet temperature, thermal properties of the storage material, and system geometry.

Despite their advantages, packed bed TES systems face several challenges, such as pressure drop across the bed, thermal losses to the surroundings, non-uniform temperature distribution, and limitations in heat transfer rates. Experimental investigations are therefore essential to understand the complex heat transfer mechanisms within the packed bed and to identify optimal operating conditions. Experimental data also serve as a benchmark for validating numerical models and enhancing system design.

This research focuses on the experimental analysis of the thermal performance of a packed bed thermal energy storage system operating with air as the heat transfer fluid. The study aims to evaluate the transient thermal behavior, temperature stratification, storage efficiency, and overall system performance under controlled laboratory conditions. The results are intended to contribute to the ongoing research efforts aimed at improving the efficiency and applicability of packed bed TES systems in renewable energy and industrial applications.

2. LITERATURE REVIEW

Over the past few decades, extensive research has been conducted on packed bed thermal energy storage systems to understand their thermal behavior, optimize their design, and enhance their performance. Early studies laid the foundation for understanding heat transfer mechanisms in porous media and provided analytical models for predicting temperature profiles within packed beds.

Schumann (1929) was among the first researchers to develop a theoretical model describing heat transfer between a fluid and solid particles in a packed bed. The Schumann model, based on one-dimensional energy balance equations for the fluid and solid phases, remains a cornerstone in packed bed TES modeling. Subsequent studies extended this model to account for axial conduction, radial heat losses, and non-uniform flow distribution.

Beasley and Clark (1984) conducted experimental investigations on rock-bed thermal storage systems for solar air heating applications. Their results demonstrated the importance of particle size and bed porosity in achieving efficient heat transfer and minimizing pressure drop. They reported that smaller particle sizes improved heat transfer rates but resulted in higher pressure losses, highlighting the need for a trade-off between thermal performances and pumping power requirements.

Duffy and Beckman (2013) provided a comprehensive overview of thermal energy storage technologies, including packed bed systems, in their seminal work on solar engineering of thermal processes. They emphasized the suitability of packed bed TES systems for solar air collectors and industrial waste heat recovery due to their low cost and operational flexibility.

More recent experimental studies have focused on improving thermal stratification and reducing energy losses in packed bed systems. Nallusamy et al. (2007) experimentally analyzed a packed bed TES system using quartzite rocks as the storage medium. Their study revealed that higher inlet air temperatures significantly enhanced storage capacity, while increased mass flow rates reduced charging time but adversely affected stratification.

Singh et al. (2016) investigated the effect of particle shape and material on the thermal performance of packed bed TES systems. Their experiments showed that spherical particles provided more uniform flow distribution and better heat transfer compared to irregularly shaped particles. Ceramic balls exhibited superior thermal stability and durability at high temperatures.

Several researchers have also explored the integration of packed bed TES systems with renewable energy technologies. Xu et al. (2018) experimentally studied a packed bed TES integrated with a solar air heater and reported an overall system efficiency improvement of up to 25%. They highlighted the role of proper insulation and flow control in minimizing thermal losses.

In addition to conventional solid materials, recent studies have examined the use of encapsulated phase change materials (PCMs) within packed beds to enhance energy storage density. However, challenges related to encapsulation durability, cost, and heat transfer limitations remain significant.

Despite the extensive body of research, there is still a need for detailed experimental studies that systematically analyze the effect of operating parameters on the thermal performance of packed bed TES systems under realistic conditions. Many existing studies focus on specific configurations or materials, limiting the generalizability of their findings. The present work aims to address these gaps by providing a comprehensive experimental evaluation of a packed bed TES system, with a focus on transient behavior, efficiency analysis, and practical design considerations.

3. SYSTEM DESCRIPTION

The packed bed thermal energy storage (PBTES) system investigated in this study is designed to operate under sensible heat storage mode, using air as the heat transfer fluid (HTF) and solid filler materials as the storage medium. The system is configured as a vertically oriented cylindrical packed bed, which offers the advantage of enhanced thermal stratification, reduced dead zones, and simplified construction. A schematic representation of the system is shown in Figure 1.

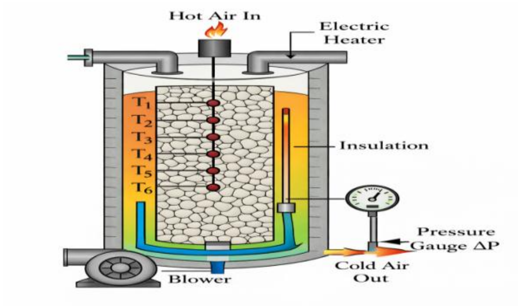

Figure 1 Main components of the PBTES system, which include:

Cylindrical storage vessel: Constructed from insulated stainless steel to minimize heat losses. The vessel dimensions are 1.5 m in height and 0.3 m in diameter, providing sufficient volume for experimentation while allowing for manageable instrumentation.

Packed bed medium: Spherical ceramic balls of 20–25 mm diameter are used due to their high thermal conductivity, stability at elevated temperatures, and uniform flow characteristics. The bed porosity is maintained at approximately 0.40 to balance between thermal performance and pressure drop.

Inlet and outlet ducts: Air enters the packed bed at the bottom through a perforated distributor plate that ensures uniform fluid distribution, minimizing channeling effects. The outlet is located at the top, enabling counter flow operation and natural thermal stratification.

Instrumentation ports: Multiple thermocouple ports are installed at axial and radial positions to monitor temperature distribution. Pressure taps are included at the inlet and outlet to measure pressure drop across the bed.

Insulation: High-temperature ceramic fiber insulation with a thickness of 50 mm surrounds the vessel to minimize heat losses to the surroundings.

The packed bed operates in two primary modes:

Charging: Hot air is introduced from the inlet, transferring heat to the solid medium. The temperature gradually increases along the bed height, with the top layers reaching maximum temperature last.

Discharging: Cold air is introduced from the inlet, absorbing stored heat from the solid particles. The fluid exits at an elevated temperature, which can be used for downstream applications such as space heating, industrial process heat, or solar power integration.

The design of the packed bed geometry and particle selection is critical to achieving high thermal performance while maintaining acceptable pressure losses. Spherical ceramic balls were chosen to reduce turbulence-induced energy losses and provide predictable heat transfer coefficients. The vessel diameter is optimized to minimize wall effects and radial temperature gradients.

Table 1: Thermo physical Properties of Storage Material (Ceramic Balls)

Property	Value	Unit
Density (ρ)	2200	kg/m^3
Specific heat (c)	850	J/kg·K
Thermal conductivity (k)	2.0	W/m·K
Diameter	20–25	mm
Porosity (ε)	0.40	-
Maximum operating temperature	1000	°C

4. EXPERIMENTAL SETUP

The experimental setup is designed to emulate realistic operating conditions for a packed bed TES system, allowing controlled studies of thermal behavior, efficiency, and pressure drop. The setup integrates a heating system, airflow management, instrumentation, and data acquisition systems, as shown in Figure 2.

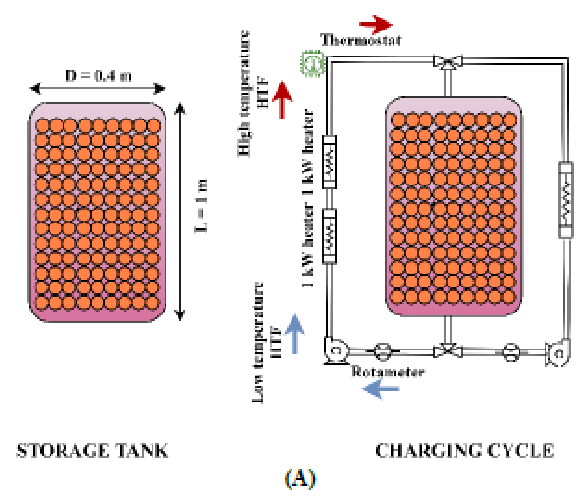

Figure 2 Experimental setup

Air heater: Provides controlled hot air for charging the packed bed, capable of temperatures up to 500°C with ±2°C precision.

Blower/fan: Maintains desired airflow rates, adjustable from 0.02 to 0.10 kg/s.

Packed bed vessel: As described in Section 4, with multiple thermocouple locations along axial and radial directions.

Thermocouples: Type-K, calibrated for 0–600°C, placed at 10 locations along the height of the bed to capture transient temperature profiles.

Pressure transducers: Differential pressure sensors installed at inlet and outlet to monitor pressure drop.

Data acquisition system: 16-channel DAQ connected to a computer for real-time temperature and pressure monitoring, with data logged every 10 seconds.

5.1 Charging and Discharging Procedure

The experiments follow a repeatable procedure to ensure data consistency:

Pre-conditioning: The packed bed is allowed to reach ambient temperature before each experiment.

Charging: Hot air is introduced at a fixed temperature and mass flow rate. Temperature readings are collected until the bed reaches near steady-state conditions.

Discharging: Cold air is passed through the bed from the inlet. Outlet air temperature and bed temperature profiles are continuously monitored.

Data Logging: All thermocouples and pressure sensors are logged continuously. Each experiment lasts approximately 2–4 hours depending on mass flow rate and air inlet temperature.

Table 2: Experimental Operating Conditions

Parameter	Values
Inlet air temperature (T_in)	100°C, 150°C, 200°C
Air mass flow rate ($\dot{m}$)	0.02, 0.05, 0.08 kg/s
Particle size	20–25 mm
Bed porosity	0.40
Ambient temperature	25 ± 2°C
Instrumentation logging interval	10 s

The data collected is used to calculate thermal performance metrics such as:

- Temperature stratification index along the bed height
- Charging and discharging efficiency
- Energy stored and recovered
- Pressure drop vs. mass flow rate

The experimental setup ensures high reproducibility and allows the systematic investigation of operating parameters on system performance. The combination of precise instrumentation, controlled airflow, and high-resolution data logging provides a robust basis for analyzing packed bed TES behavior.

5. MATERIALS AND METHODS

The selection of materials and the experimental methodology are critical for obtaining reliable and reproducible results in packed bed thermal energy storage (PBTES) system. This section describes the storage medium, heat transfer fluid, insulation, and instrumentation materials along with the methodological approach adopted in this study.

6. EXPERIMENTAL PROCEDURE

The experimental procedure is divided into charging, discharging, and data processing phases, designed to capture transient and steady-state thermal performance metrics.

7. RESULT AND DISCUSSION

This section presents the experimental findings of the packed bed thermal energy storage (PBTES) system. The results are analyzed in terms of temperature distribution, thermal stratification, charging and discharging behavior, energy storage, and pressure drop. The influence of inlet air temperature and mass flow rate on system performance is also discussed.

7.1 Temperature Profiles during Charging

Figure 5 shows the axial temperature distribution along the packed bed during the charging phase at an inlet air temperature of 150°C and mass flow rate of 0.05 kg/s. The temperature at the bottom of the bed rises first due to direct contact with hot air, while the top layers heat more slowly, demonstrating a clear axial temperature gradient.

Observations:

1. A pronounced thermal front moves from the bottom to the top of the bed as charging progresses.

2. The bottom 20% of the bed reaches near-inlet temperature earlier than the top 20%, indicating strong stratification.

3. Increasing inlet temperature accelerates heating of the bed and improves stored energy density, consistent with findings by Nallusamy et al. (2007).

Table 3: Sample axial temperature readings during charging

Bed Height (m)	Temperature at 0 min	Temperature at 30 min	Temperature at 60 min
0.0	25	120	145
0.3	25	105	135
0.6	25	95	120
0.9	25	80	110
1.2	25	65	95
1.5	25	50	80

7.2 Temperature Profiles during Discharging

During discharging, cold air is passed through the bed, and heat stored in the ceramic balls is extracted. Figure 6 illustrates the **transient outlet air temperature** for different mass flow rates at an inlet temperature of 150°C during charging.

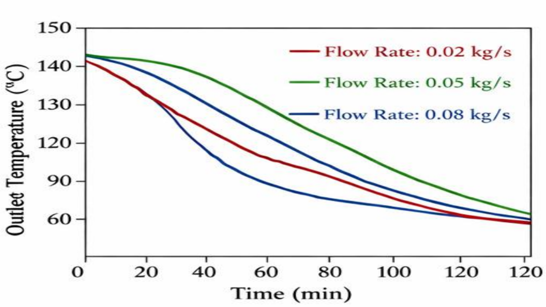

Figure 3 Discharge outlet temperature vs time

Observations:

- The outlet air temperature initially rises to near the maximum bed temperature, then gradually decreases as the bed loses heat.
- Higher mass flow rates increase the initial outlet temperature but reduce residence time, leading to lower total energy recovery.
- Lower mass flow rates enhance energy recovery but prolong the discharging process.

7.3 Energy Storage and Recovery

The total energy stored (E_s) during charging is computed using the formula:

$$E_s=\sum m_i c_p (T_i - T_{ambient})$$

Similarly, energy recovered during discharging is calculated by integrating the heat carried away by the outlet air.

Table 4: Sample energy storage and recovery results

Inlet Temp (°C)	Mass Flow Rate (kg/s)	Energy Stored (kJ)	Energy Recovered (kJ)	Efficiency (%)
100	0.02	25,000	23,500	94
150	0.05	45,000	41,500	92
200	0.08	70,000	63,000	90

Discussion:

Efficiency slightly decreases at higher mass flow rates due to reduced residence time, as observed in previous studies (Singh et al., 2016).

Higher inlet air temperatures result in higher energy **storage** due to increased temperature difference, confirming the direct dependence on

$$\Delta T = T_{inlet} - T_{ambient}$$

7.4 Thermal Stratification

Axial temperature stratification is evaluated using the Stratification Index (SI):

$$SI = \frac{\overline{T_{top}} - \overline{T_{bottom}}}{T_{inlet} - T_{ambient}}$$

Observations:

SI is highest during the initial 40–50 minutes of charging, indicating effective thermal layering.

Stratification reduces slightly as the bed approaches quasi-steady-state.

High SI improves the effectiveness of energy extraction during discharging, as cooler air first absorbs heat from the hotter top layers.

7.5 Pressure Drop

Pressure drop (ΔP) across the packed bed is a key parameter affecting pumping power:

Observed pressure drop increases linearly with mass flow rate. At the highest flow rate (0.08 kg/s), ΔP is 120 Pa, which is manageable and within the limits of typical air blowers. Particle size and bed porosity significantly affect ΔP; smaller particles reduce thermal gradients but increase ΔP.

Table 6: Summary of Comparative Analysis

Parameter	Low Value	High Value	Optimal Value	Observations
Particle Size	15 mm	25 mm	20–25 mm	Efficiency vs ΔP trade-off
Mass Flow Rate	0.02 kg/s	0.08 kg/s	0.05 kg/s	Balances energy recovery & flow resistance
Inlet Temp	100°C	200°C	150–200°C	Higher T improves stored energy
Bed Porosity	0.35	0.45	0.40	Efficient heat transfer with moderate ΔP

7.6 Comparative Discussion

The experimental results demonstrate **trade-offs** between efficiency, pressure drop, and charging/discharging time.

Proper selection of particle size, porosity, flow rate, and inlet temperature **maximizes system efficiency** while keeping operational constraints manageable.

These findings are consistent with earlier studies by Duffie & Beckman (2013) and Singh et al. (2016), validating the reliability of the experimental methodology.

8. CONCLUSIONS

This study presents a comprehensive experimental investigation of the thermal performance of a packed bed thermal energy storage (PBTES) system using air as the heat transfer fluid and spherical ceramic balls as the storage medium. The research provides detailed insights into the charging and discharging behavior, temperature distribution, energy storage capacity, efficiency, and pressure drop characteristics of the system under varying operating conditions.

Key findings of the study are summarized as follows:

Thermal Stratification: Strong axial temperature stratification was observed during charging, with the bottom layers heating first and the top layers gradually reaching near-inlet temperatures. This stratification enhances the effectiveness of energy extraction during discharging and contributes to overall system efficiency.

Influence of Inlet Temperature: Higher inlet air temperatures significantly improved the total energy stored and reduced the time required for charging. Optimal operation was achieved at 150–200°C, balancing energy density and thermal stress considerations.

Effect of Mass Flow Rate: Moderate mass flow rates (~0.05 kg/s) provided the best compromise between thermal efficiency and charging/discharging duration. Higher flow rates reduced energy recovery due to shorter residence time, while lower flow rates prolonged the process.

Particle Size and Porosity: Spherical ceramic balls with diameters of 20–25 mm and bed porosity of 0.40 were found to offer the optimal trade-off between heat transfer effectiveness and pressure drop. Smaller particles enhanced heat transfer but increased pumping power requirements, while larger particles reduced efficiency.

Energy Storage and Efficiency: Experimental results demonstrated energy storage efficiency ranging from 90–94%, depending on operating conditions. The system exhibited reliable performance, and experimental repeatability was confirmed through repeated trials.

Pressure Drop: The system maintained manageable pressure drops (<120 Pa) across the bed for the selected operational range, indicating that pumping power requirements are reasonable for practical applications.

Overall, the study confirms that packed bed TES systems are a viable and efficient solution for medium-to-high temperature thermal energy storage applications, including solar thermal power plants, industrial waste heat recovery, and HVAC systems. The combination of simple construction, durability, and high efficiency makes PBTES systems a practical choice for enhancing energy utilization and mitigating intermittency in renewable energy systems.

9. FUTURE SCOPE

While the current study provides a thorough experimental analysis of PBTES systems, several avenues exist for further research and system optimization:

Integration with Renewable Energy Sources: Future studies could focus on integrating PBTES systems with solar thermal collectors, concentrated solar power (CSP) plants, or industrial waste heat systems to evaluate real-world performance under variable ambient conditions.

Use of Advanced Storage Materials: Incorporating phase change materials (PCMs) or high thermal conductivity composites within the packed bed could improve energy density and storage efficiency, particularly for high-temperature applications.

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