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Performance Evaluation of Sensible and Phase Change Thermal Energy Storage Materials in Solar Thermal Systems

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Abstract

Solar thermal energy systems play a significant role in renewable energy utilization by converting solar radiation into thermal energy. However, the intermittent nature of solar radiation creates challenges in maintaining continuous energy supply. Thermal Energy Storage (TES) systems help overcome this limitation by storing excess heat during periods of high solar radiation and releasing it when needed. Two major TES techniques used in solar thermal systems are sensible heat storage and phase change material (PCM) storage. Sensible heat storage involves storing thermal energy through temperature change of materials such as water, rocks, sand, or molten salts, while PCM storage relies on latent heat during phase transitions. This paper presents a comprehensive evaluation of both TES systems, including their working principles, materials used, performance characteristics, advantages, limitations, and applications in solar thermal systems. A comparative analysis highlights the effectiveness of PCMs in achieving higher energy storage density, while sensible storage systems offer simplicity and cost effectiveness. The study concludes with recommendations for improving thermal storage efficiency in solar energy applications.

Introduction

The increasing global demand for energy and the environmental impacts associated with fossil fuels have accelerated the adoption of renewable energy technologies. Among these technologies, solar thermal systems are widely used for applications such as water heating, space heating, industrial processes, and power generation.

One of the main challenges associated with solar energy is its intermittent and unpredictable nature. Solar radiation is available only during daylight hours and varies with weather conditions. This limitation makes energy storage an essential component in solar thermal systems.

Thermal Energy Storage (TES) technologies allow excess heat collected during peak solar radiation periods to be stored and utilized later when solar input is unavailable. TES improves system efficiency, reliability, and energy management.

There are three major categories of TES:

1. Sensible Heat Storage (SHS)
2. Latent Heat Storage using Phase Change Materials (PCMs)
3. Thermochemical Energy Storage

This study focuses primarily on sensible heat storage and PCM-based latent heat storage, as these are the most widely used methods in solar thermal systems.

Thermal Energy Storage in Solar Systems

Thermal Energy Storage systems store heat for later use and play a critical role in improving the efficiency and performance of solar thermal systems.

The main objectives of TES are:

- Storing excess thermal energy
- Balancing energy supply and demand
- Improving system efficiency
- Providing continuous thermal energy even without sunlight

TES systems are typically integrated into solar collectors, solar water heaters, solar power plants, and building heating systems.

Sensible Heat Thermal Energy Storage

Sensible Heat Thermal Energy Storage (SHS) is one of the most widely used methods of storing thermal energy in solar thermal systems. In this method, heat is stored by raising the temperature of a storage material without changing its physical phase. The amount of heat stored depends on the mass of the material, its specific heat capacity, and the temperature difference during the charging and discharging processes. Common materials used for sensible heat storage include water, rocks, sand, concrete, and molten salts, as these materials can absorb and release large amounts of heat when their temperature changes. Among these, water is the most commonly used medium due to its high heat capacity, low cost, and easy availability. Sensible heat storage systems are relatively simple in design, reliable in operation, and cost-effective compared to other thermal energy storage methods. They are widely applied in solar water heating systems, solar air heating systems, and concentrated solar power plants. However, one limitation of sensible heat storage is its relatively low energy storage density, which requires larger storage volumes to store significant amounts of thermal energy. Despite this limitation, sensible heat storage remains an important and practical technology for improving the efficiency and reliability of solar thermal systems.

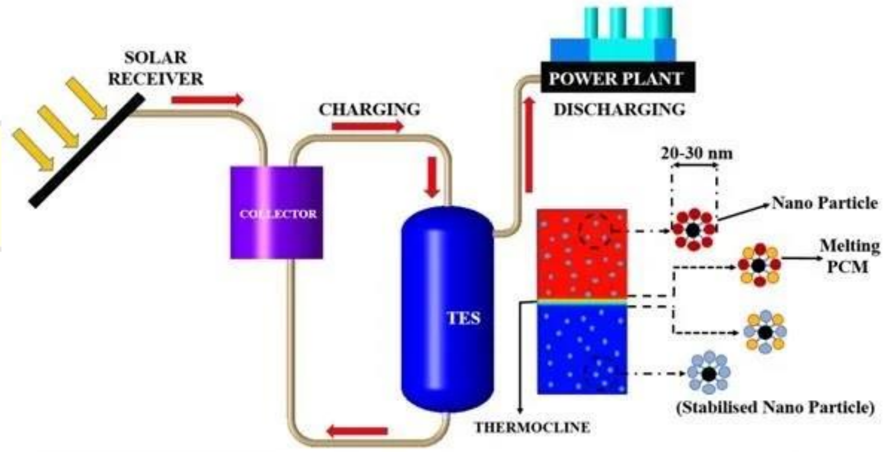

Figure: Sensible heat thermal storage system

Principle of Sensible Heat Storage

Sensible heat storage works by increasing the temperature of a storage medium without changing its phase. The stored heat depends on the temperature change and heat capacity of the material.

The amount of heat stored is given by:

$$Q = mC_p(T_2 - T_1)$$

Where:

- Q = Heat stored (J)
- m = Mass of storage material (kg)
- Cp = Specific heat capacity (J/kg·K)
- T1 = Initial temperature
- T2 = Final temperature

The larger the temperature difference and specific heat capacity, the greater the energy storage.

Materials Used in Sensible Heat Storage

Common materials used include:

Water

Water is the most widely used sensible heat storage medium due to its high heat capacity and low cost.

Advantages:

- High specific heat capacity
- Easily available
- Non-toxic

Applications:

- Solar water heaters
- Residential heating systems

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Rocks and Pebbles

Rocks are commonly used in solar air heating systems.

Advantages:

- Low cost
- Good thermal stability

Disadvantages:

- Lower heat storage capacity compared to water

Molten Salts

Molten salts are commonly used in concentrated solar power (CSP) plants.

Advantages:

- High operating temperature
- Good thermal stability

Applications:

- Solar power tower plants
- Industrial heat storage

Advantages of Sensible Heat Storage

- Simple technology
- Low material cost
- Easy design and operation
- Reliable performance

Limitations of Sensible Heat Storage

- Low energy storage density
- Requires large storage volume
- Heat losses can occur over time

Phase Change Material (PCM) Thermal Energy Storage

Principle of PCM Storage

Phase Change Materials store energy through latent heat during phase transitions, typically from solid to liquid or liquid to solid.

During the phase change process, the temperature remains nearly constant while the material absorbs or releases large amounts of heat.

The stored heat is expressed as:

$$Q = mL$$

Where:

- Q = Heat stored
- m = Mass of PCM
- L = Latent heat of fusion

Types of Phase Change Materials

PCMs are classified into three categories:

Organic PCMs

Examples:

- Paraffin wax
- Fatty acids

Advantages:

- Chemical stability
- Non-corrosive
- Long life cycle

Disadvantages:

- Low thermal conductivity

Inorganic PCMs

Examples:

- Salt hydrates
- Metallic alloys

Advantages:

- High latent heat
- Higher thermal conductivity

Disadvantages:

- Corrosion issues
- Phase segregation

Eutectic PCMs

These are mixtures of different compounds that melt and solidify at a specific temperature.

Advantages:

- Sharp melting point
- Good thermal properties

Advantages of PCM Storage

- High energy storage density
- Nearly constant temperature during storage
- Reduced storage volume
- Suitable for temperature-controlled applications

Limitations of PCM Storage

- Higher cost compared to sensible storage
- Low thermal conductivity
- Possible phase segregation
- Need for encapsulation technology

Performance Evaluation of Sensible and PCM Storage Systems

Energy Storage Density

PCM systems typically store 5–14 times more energy per unit volume compared to sensible heat storage.

Thermal Efficiency

PCM systems maintain nearly constant temperature during charging and discharging, which improves thermal efficiency.

Sensible systems experience continuous temperature variation.

Heat Transfer Rate

Sensible heat systems usually have better heat transfer characteristics, while PCMs require heat transfer enhancement techniques such as:

- Fins
- Metal matrices
- Graphite additives

Cost Comparison

Sensible heat storage is generally cheaper because materials such as water and rocks are inexpensive.

PCM systems have higher costs due to:

- Material cost
- Encapsulation technology
- Heat transfer enhancement systems

Applications in Solar Thermal Systems

Solar Water Heating Systems

Both sensible storage (water tanks) and PCMs are used for domestic hot water applications.

Solar Air Heating Systems

Pebble bed sensible storage systems are commonly used.

Concentrated Solar Power Plants

Molten salt sensible heat storage is widely used for storing heat in solar power towers.

Building Thermal Management

PCMs are integrated into building materials to regulate indoor temperatures.

Recent Research Developments

Recent advancements in TES technologies include:

- Nano-enhanced phase change materials
- Encapsulated PCM systems
- Hybrid sensible–latent storage systems
- Thermal conductivity enhancement using graphene and metal foams

These innovations aim to improve efficiency, reduce cost, and enhance heat transfer performance.

Future Scope

Future research in TES systems focuses on:

- Developing low-cost high-performance PCMs
- Improving thermal conductivity
- Designing hybrid TES systems
- Integrating TES with smart solar grids
- Enhancing long-term stability of storage materials

Conclusion

Thermal Energy Storage plays a vital role in improving the reliability and efficiency of solar thermal systems. Sensible heat storage systems are simple, cost-effective, and widely used in many applications. However, they have lower energy storage density and require larger storage volumes.

Phase Change Materials offer significant advantages due to their high energy storage density and ability to maintain nearly constant temperature during phase change. Despite their higher cost and technical challenges, PCM-based storage systems are becoming increasingly important in modern solar energy applications.

A hybrid combination of sensible heat storage and PCM technology can provide an effective solution for maximizing thermal energy storage performance in solar thermal systems.

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