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THERMAL ENERGY STORAGE IN EVACUATED TUBE COLLECTORS (ETCS)

Ankit Jain[1], Dr. Sangram Bana[2]

ABSTRACT

The inherent intermittency of solar radiation necessitates the integration of robust Thermal Energy Storage (TES) systems to ensure a continuous energy supply. Evacuated Tube Collectors (ETCs) represent a high-efficiency solar thermal technology capable of operating at medium-to-high temperatures due to minimized convective heat losses. This review provides an exhaustive analysis of the integration of TES within ETCs, transitioning from conventional Sensible Thermal Energy Storage (STES) to advanced Latent Heat Thermal Energy Storage (LHTES) using Phase Change Materials (PCMs). We examine the thermophysical properties of storage media, heat transfer enhancement techniques—including the use of fins, metal foams, and nanofluids—and the thermodynamic evaluation of these systems through energy and exergy lenses. The paper synthesizes findings from over 50 seminal and recent studies to outline the current state-of-the-art, economic viability, and future research trajectories in solar thermal harvesting.

[1] Research Scholar, Department of Mechanical Engineering, Phonics University
[2] Associate Professor, Phonics University

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1. INTRODUCTION TO SOLAR THERMAL ENERGY AND THE ROLE OF ETCS

The global transition toward sustainable energy systems is heavily reliant on solar thermal technologies. Among the various collector types, the Evacuated Tube Collector (ETC) has gained prominence for its ability to provide high-grade heat even in cold or cloudy climates [1]. The fundamental advantage of the ETC lies in its vacuum-sealed double-glass tube structure, which virtually eliminates convective and conductive heat losses to the ambient environment [2].

However, the primary limitation of solar energy is its temporal mismatch between supply (daylight) and demand (evening/ night). To bridge this gap, Thermal Energy Storage (TES) is integrated into the collector loop. In-situ storage—where the storage medium is placed directly within the collector tubes—minimizes the footprint and reduces the thermal losses associated with external piping and tanks [3]. This review explores how different storage mechanisms and materials are engineered to optimize the performance of ETC systems.

2. FUNDAMENTALS OF EVACUATED TUBE COLLECTORS (ETCS)

The efficiency of an ETC is governed by its ability to absorb solar radiation and retain it within a vacuum envelope. There are three primary configurations used in TES integration:

2.1 Water-in-Glass (WiG) Collectors

In this design, the solar-absorbing fluid (usually water) flows directly into the glass tubes. The water itself acts as the storage medium [4]. While simple and cost-effective, these systems are prone to scaling and freezing in cold climates [18].

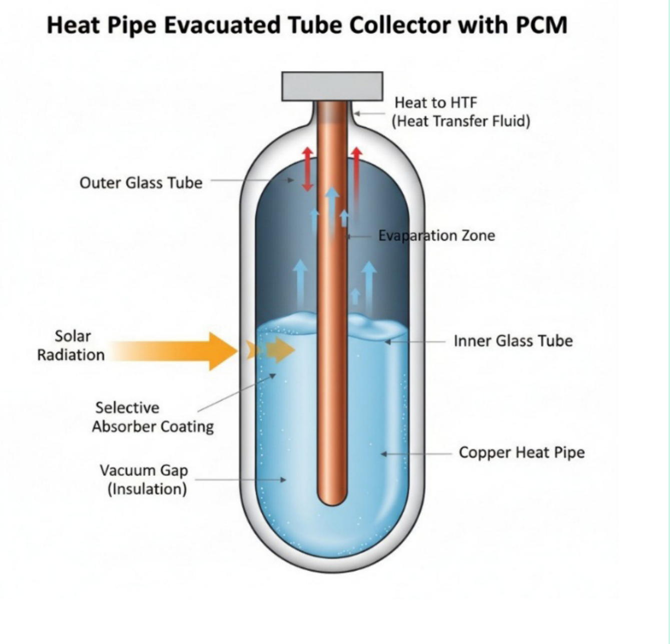
2.2 Heat Pipe ETCs (HP-ETC)

A heat pipe consists of a sealed copper tube containing a small amount of working fluid (e.g., ethanol or water). When heated, the fluid evaporates, rises to the condenser tip, releases heat to the manifold, and condenses back to the bottom [21]. Integrating PCMs around the heat pipe allows for significant energy storage within the tube volume [27].

2.3 U-Tube ETCs

A copper U-shaped pipe is inserted into the evacuated tube. A heat transfer fluid (HTF) circulates through the U-tube. The space between the U-tube and the glass wall can be filled with a storage medium like PCM to provide thermal buffering [43].

Fig. 1: U-Tube ETC



3. PRINCIPLES OF THERMAL ENERGY STORAGE (TES)

TES systems are classified based on the physical state and the mechanism of energy retention.

3.1 Sensible Thermal Energy Storage (STES)

STES relies on the temperature increase of a material. The amount of stored energy Q_s is calculated as:

$$Q_s = \int_{T_i}^{T_f} m \cdot c_p(T)\, dT$$

Where:
m is the mass of the storage medium (kg).
c_p is the specific heat capacity (J· kg^{-1}· K^{-1}).
T_i and T_f are the initial and final temperatures (K).

3.2 Latent Heat Thermal Energy Storage (LHTES)

LHTES utilizes the energy absorbed or released during a phase transition (usually solid-to-liquid). The total energy stored Q_L includes sensible heat of the solid phase, the latent heat of fusion, and the sensible heat of the liquid phase:

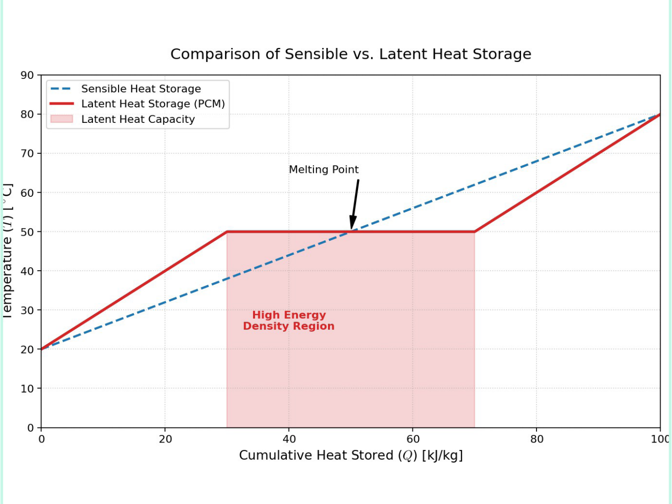
$$Q_L = m\left[c_{p,s}(T_m - T_i) + L + c_{p,l}(T_f - T_m)\right]$$

Where:
L is the latent heat of fusion (J· kg^{-1}).
T_m is the melting temperature (K).

Subscripts s and l denote solid and liquid phases, respectively.

LHTES systems are preferred for ETCs because they offer high energy density and provide heat at a nearly constant temperature, which is critical for maintaining high exergy [14].

Fig. 2: Comparison plot of Sensible Heat storage and Latent Heat Storage Systems



4. STORAGE MATERIALS IN ETCS

The choice of material determines the operating range and efficiency of the system.

4.1 Sensible Media

Water: High c_p, but limited to 100°C at atmospheric pressure [1].

Thermic Oils: Used for high-temperature applications but have lower c_p and higher costs [28].
Nanofluids: Adding nanoparticles (e.g., Al_2O_3, CuO) to water or oil increases the thermal conductivity

and absorption coefficient [39].

4.2 Phase Change Materials (PCMs)

PCMs are categorized into three groups:

1. **Organic (Paraffins and Fatty Acids):** Non-corrosive, chemically stable, but possess low thermal conductivity ($\approx 0.2\ W\cdot m^{-1}\cdot K^{-1}$) [11].
2. **Inorganic (Salt Hydrates):** High latent heat and higher thermal conductivity, but suffer from sub cooling and phase segregation [31].
3. **Eutectics:** Mixtures of two or more components that melt and freeze congruently [50].

Table 1: Comparison of Common Storage Materials for ETC Integration

Material	Type	T_m (°C)	L (kJ·kg^{-1})	k (W·m^{-1}·K^{-1})	Ref
Water	Sensible	N/A	N/A	0.60	[1]
Paraffin RT50	Organic PCM	45 – 51	160	0.20	[4]
$CaCl_2\cdot 6H_2O$	Salt Hydrate	29	190	1.08	[14]
Erythritol	Sugar Alcohol	118	340	0.73	[31]
Stearic Acid	Fatty Acid	69	200	0.17	[11]

5. HEAT TRANSFER ENHANCEMENT TECHNIQUES

The low thermal conductivity of organic PCMs is the "bottleneck" of LHTES in ETCs. Several techniques are employed to accelerate the charging (melting) and discharging (solidification) rates.

5.1 Extended Surfaces (Fins)

Fins increase the surface area for heat transfer. In an ETC, longitudinal or circular fins are often attached to the heat pipe or U-tube [8].

Effectiveness: Siahpush et al. [7] demonstrated that internal fins could reduce the melting time by over 50%.

5.2 Metal Foams

High-porosity metal foams (e.g., copper or aluminum) are impregnated with PCM. The continuous metal matrix provides a high-conductivity path throughout the storage volume [15].

5.3 Nanoparticle-Enhanced PCM (NePCM)

Dispersing high-conductivity nanoparticles (e.g., Carbon Nanotubes, Al_2O_3) into the PCM creates a NePCM. This improves the effective thermal conductivity k_{eff} [37]:

$$k_{\mathrm{eff}} = \frac{k_p\left(k_{np} + 2k_p - \phi(k_{np} - k_p)\right)}{k_{np} + 2k_p + 2\phi(k_{np} - k_p)}$$

Where:

k_p and k_{np} are the conductivities of the PCM and nanoparticle.

ϕ is the volume fraction of nanoparticles.

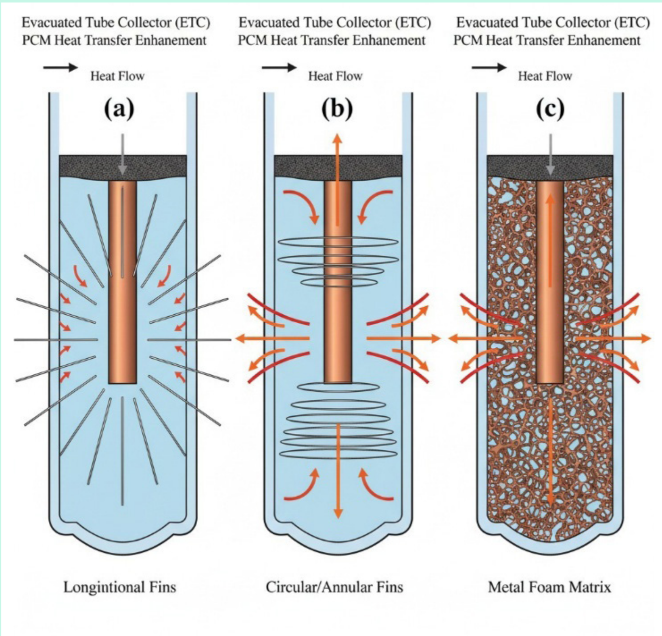


Fig. 3: Schematic longitudinal, circular fins and Metal Foams ETCs

6. MATHEMATICAL MODELING AND PERFORMANCE METRICS

The performance of an integrated ETC-TES system is evaluated using the First and Second Laws of Thermodynamics.

6.1 Energy Efficiency (η_{en})

The energy efficiency is the ratio of the useful heat gained by the HTF to the total solar energy incident on the collector:

$$\eta_{en} = \frac{\int \dot{m} c_p (T_{\mathrm{out}} - T_{\mathrm{in}})\, dt}{\int A_c \int G\, dt}$$

Where:
$\dot{m}$ is the mass flow rate (kg· s^{-1}).
A_c is the collector aperture area (m^2).
G is the solar irradiance (W· m−2).

6.2 Exergy Efficiency (η_{ex})

Exergy analysis accounts for the quality of energy. It is particularly useful for TES because it penalizes the temperature drop during storage [29]:

$$\eta_{ex} = \frac{Exergy\ Recovered}{Exergy\ Input}$$

The exergy of the solar radiation is often modeled using the Petela's formula:

$$\psi = G \cdot A_c \left[1 - \frac{4}{3}\left(\frac{T_{\text{amb}}}{T_{\text{sun}}}\right) + \frac{1}{3}\left(\frac{T_{\text{amb}}}{T_{\text{sun}}}\right)^4\right]$$

where:

- G is the
- solar irradiance
- ($\text{W} \cdot \text{m}^{-2}$).
- A is the aperture area (m^2).
- $T_{\text{sun}} \approx 5800\ \text{K}$ is the effective surface temperature of the sun.
- T_{amb} is the ambient temperature
- . For standard thermodynamic calculations, we typically assume $T_{\text{amb}} = 300\ \text{K}$.

7. SYSTEM CONFIGURATIONS AND INTEGRATION

Researchers have explored various ways to integrate PCM into ETCs:

1. **Inside the Absorber Tube:** The PCM fills the annular space between the heat pipe and the glass tube [4]. This is the most common "in-situ" method.
2. **Inside the Manifold:** The PCM is placed in the header/manifold where the heat pipe tips release heat. This provides a buffer for the HTF [6].
3. **External Storage Tank with PCM Modules:** The ETC acts as a standard collector, but the storage tank contains PCM-filled capsules to increase energy density [51].

8. CHALLENGES AND LIMITATIONS

Despite the advantages, several technical hurdles remain:

8.1 Subcooling and Hysteresis

Inorganic PCMs often require a temperature much lower than their melting point to initiate solidification. This subcooling reduces the effective temperature at which heat is recovered [31].

8.2 Thermal Stability and Corrosion

PCMs must undergo thousands of melting/freezing cycles without degrading. Furthermore, salt hydrates can be highly corrosive to the copper heat pipes or aluminum fins, necessitating protective coatings or specialized encapsulation [11].

8.3 Phase Segregation

In salt hydrates, the salt may settle at the bottom of the tube over time, leading to irreversible loss of storage capacity [14].

9. ECONOMIC AND ENVIRONMENTAL IMPACT

The integration of TES increases the initial capital cost of an ETC system. However, the Levelized Cost of Energy (LCOE) can be lower due to the increased solar fraction (the percentage of the load met by solar energy).

Payback Period: Studies suggest that PCM-integrated ETCs have a payback period of 3 to 7 years, depending on local fuel costs and solar availability [48].

CO_2 Mitigation: By extending the heating period into the night, these systems significantly reduce the reliance on fossil-fuel-based backup heaters [53].

10. CONCLUSION AND FUTURE PROSPECTS

The integration of Thermal Energy Storage in Evacuated Tube Collectors is a mature yet evolving field. The transition from sensible to latent heat storage has significantly enhanced the energy density and thermal management of solar water heaters.

Key Findings

1. **PCMs** provide a nearly isothermal heat source, which is superior for domestic hot water and space heating applications.
2. **Heat transfer enhancement** (fins and nanoparticles) is essential to overcome the low conductivity of organic PCMs.

3. **Exergy analysis** reveals that LHTES systems maintain higher energy quality compared to STES.

Future Directions:

- Development of **bio-based PCMs** to improve environmental sustainability.
- Advanced **multi-stage TES** using different PCMs with varying melting points to optimize the temperature gradient along the collector.
- Integration of **thermo-chemical storage** for long-term (seasonal) energy retention.

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