

A Comprehensive Review of Thermal Energy Storage Systems for Internal Combustion Engines: Scope and Integration in India

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ABSTRACT: The exhaustion of fossil fuels and the rising issues of environmental pollution have made it imperative to optimize the energy infrastructure across the globe. While the Internal Combustion Engine (ICE) continues to be the key prime mover for both transportation and localized electricity production, these engines are intrinsically inefficient due to their low thermodynamic efficiency, which results in the loss of around 30% of the input energy in the form of exhaust heat. In this paper, we present a detailed analysis of (Thermal Energy Storage) TES technologies, particularly (Latent Heat Thermal Energy Storage) LHTES using (Phase Change Materials) PCMs, in order to control the wastage of heat in exhaust. This review highlights some major shortcomings that are prevalent in the current body of literature through the analysis of material stability, heat transfer enhancement, CFD optimization, exergy analysis, and emission mitigation. Finally, we discuss the extensive opportunities and technological feasibility of adopting TES in India's rapidly growing industries, agriculture, and commercial applications.

KEYWORDS: Thermal Energy Storage, Exergy Analysis, Phase Change Materials, Internal Combustion Engine, Waste Heat Recovery, Emission Control, India.

I. INTRODUCTION

The combination of climate change issues, strict emission regulations, and fast depletion of traditional fossil fuels has made efficient use of energy an important global concern. Internal Combustion Engine (ICE) working on either diesel or gasoline is one of the major engines that can neither be substituted nor replaced yet by any other engine in industries and automobiles. But ICEs are inherently limited by thermodynamic laws in their performance and utilize only about 35 percent of energy content of fuel while the rest gets wasted in form of heat: 30 percent is exhausted out through gases, 28 percent via the cooling mechanism, and 7 percent via frictional losses [12, 20]. Exhaust gases have higher temperatures and relatively large flows which make them potential sources of significantly high amount of thermal energy. Capturing the exhaust gas makes sense since its reutilization leads not only to improvement in system efficiency but also reduces thermal pollution. Thermal Energy Storage Technologies provide a vital link in controlling transient thermal energy for its delayed utilization [10]. This paper is focused upon Latent Heat Thermal Energy Storage Systems, their optimization, thermodynamic evaluation, and their strategic application in India.

II. CLASSIFICATION OF TES AND MATERIAL SELECTION

Thermal Energy Storage techniques can be classified as Sensible Heat Storage, Latent Heat Storage, and Thermochemical Storage.

Sensible Heat Storage: Heat is stored in the material by raising its temperature without changing its phase. The heat gained by the material or Thermal Energy Stored is given by;

$$Q_{\text{Sensible}} = mc\Delta T$$

Where; m = mass of material;
 c = specific heat of Material
 ∇T = change in the temperature of the material due to absorption of heat

Latent Heat Storage: The energy is stored during the phase change of the material. The energy stored by the material is given by:

$$Q_{\text{Latent}} = m\nabla h$$

Where; m = mass of material;
 ∇h = change in the specific enthalpy of the material during phase change.

Thermochemical Storage: The energy is stored in the form of chemical potential energy through reversible reactions (exothermic/endothermic). The amount of thermal energy is given by;

$$Q_{\text{Therchem}} = n\nabla H_{\text{Reaction}}$$

Where; n = number of mole of reactants;
 $\nabla H_{\text{Reactants}}$ = change in the enthalpy during reaction.

The most efficient technique for recovering thermal energy from ICE exhaust gases is LHTES based on Phase Change Materials (PCM) due to its high volumetric energy storage capacity and isothermal heat absorption/rejection [4, 21]. The efficiency of a LHTES cycle strongly depends on the thermo-physical characteristics of the chosen PCM. Basic research has indicated the following main pros and cons related to PCM selection:

1. Organic PCMs (e.g., Paraffin Wax, Esters): High chemical stability, non-corrosive nature, and zero supercooling effect but low thermal conductivity [7, 11].
2. Inorganic PCMs (e.g., Salt Hydrates, Metallics): Higher latent heat density and thermal conductivity, but very corrosive and phase segregating [15].

Current experimental data indicate that despite the fact that some PCMs exhibit thermal stability at medium temperature levels (120-150°C), corrosion becomes the main failure cause for the interaction between the PCM and commonly used industrial materials such as aluminum and carbon steel. Long-term system operation requires the use of stainless steel casing or anti-corrosive coating layers [13].

Table 1: Comparative Thermo-physical Properties of Phase Change Materials (PCMs) for Waste Heat Recovery

Classification	Common Examples	Melting Temp Range (°C)	Thermal Conductivity (W/m·K)	Key Advantages	Primary Disadvantages
Organic	Paraffin Waxes, Esters	0 – 150	Low (0.15 – 0.30)	Chemically stable, no supercooling, highly recyclable.	Low thermal conductivity; flammable.
Inorganic	Salt Hydrates, Metallics	30 – 800	High (0.50 – 50.0)	High latent heat density, compact volume.	Prone to phase segregation, highly corrosive.
Eutectics	Organic-Organic mixtures	Varies	Medium	Sharp melting points, tailorable properties.	Higher material cost, complex preparation.

III. ENHANCING THERMAL PERFORMANCE VIA GEOMETRIC MANIPULATION AND CFD SIMULATION

Inherent problems in the implementation of organic PCMs include the low thermal conductivity, which drastically hinders heat transfer during rapid engine operation.

3.1. Heat Transfer Enhancements

In order to offset the natural low thermal conductivity associated with PCMs, a lot of effort has been put into heat transfer augmentation through passive methods. In essence, passive heat transfer techniques seek to optimize the heat transfer area within the storage component by utilizing the high thermal conductivity of metallic components alongside complicated geometric shapes. This includes the incorporation of high conductive metal structures such as longitudinal and annular fins and metal foams [8]. The utilization of such geometrical features poses an inherent conflict of design when considering energy storage within the heat exchanger structure. Due to the constant volume within which heat transfer takes place, increased use of metallic fins and foams translates to a reduction in the PCM volume. Thus, although the process of heat transfer is greatly enhanced, the amount of energy that can be stored is reduced.

Table 2: Summary of Heat Transfer Enhancement Techniques in LHTES Systems

Enhancement Technique	Mechanism of Action	Impact on Thermal Performance	Drawbacks for ICE Integration
Longitudinal/Annular Fins	Increases effective surface area between tubes and PCM.	Significantly accelerates melting/solidification fronts.	Decreases the volumetric fraction of PCM, reducing total energy storage capacity.
Metal Foams (Copper/Aluminum)	Creates a continuous, highly conductive 3D matrix inside the PCM.	Drastically improves thermal conductivity and temperature uniformity.	High manufacturing cost; creates localized pressure drops; prone to corrosion.
Nanoparticle Dispersion	Seeds high-conductivity particles (e.g., Al ₂ O ₃ , CuO) directly into organic PCMs.	Enhances base PCM conductivity without massive volume loss.	Particles tend to agglomerate and settle over repeated melting/cooling cycles.

3.2. CFD Simulation

It is clear that the modern method in engineering design has been the numerical prediction of performance before building prototypes. CFD analysis can be used to optimize heat transfer within shell-and-tube heat exchangers [6, 11]. In this process, the optimization of the heat transfer rate and PCM filling ratio is possible by optimizing the fin size, spacing, and tube arrangement.

IV. THERMODYNAMIC ASSESSMENT: THE NEED FOR EXERGY

The conventional approach to energy assessment (which relies on the First Law of Thermodynamics) measures the amount of heat captured; however, it does not take into consideration the quality and utility of this heat energy. In the case of high-temperature heat recovery, the Exergy approach (Second Law-based) becomes essential [3, 14].

Exergy assessment pinpoints the exact points of thermodynamic irreversibility (entropy production) in an LHTES system. Research studies comparing diesel-PHM systems indicate that the exergetic efficiency often falls considerably short of the energetic efficiency, thus revealing the deteriorating quality of heat energy during its transmission across a finite temperature difference [1, 19].

For the assessment of environmental and thermodynamic sustainability, Ecological Function (E) is considered; this function is expressed as follows:

$$E = P - T_L S_g$$

Where; P is the power output or recovered exergy, T_L is the temperature of the environment, and S_g is the entropy generation rate. Ensuring the maximization of E maximizes the amount of useful work done, ensuring minimum thermodynamic wastage. Additionally, concepts such as Effective Exergetic Performance Coefficient [5] and cascade arrangements of PCMs [23] offer remarkable potential for mitigating temperature differences and minimizing exergy loss.

Table 3: First Law (Energy) vs. Second Law (Exergy) Analysis in Exhaust Heat Recovery

Parameter	First Law Analysis (Energy)	Second Law Analysis (Exergy)
Primary Focus	Quantity of heat conserved.	Quality and work potential of heat.
Metric Calculated	Thermal Efficiency (η_{th}).	Exergetic Efficiency (η_{ex}) & Entropy Generation ($S'g$).
Treatment of Losses	Treats all heat losses equally, regardless of temperature.	Penalizes heat losses across large temperature gradients (irreversibilities).
System Optimization	Maximizes heat capture.	Minimizes exergy destruction and maximizes the Ecological Function (E).

V. EMISSIONS CONTROL: LHTES AS "THERMAL BATTERIES"

In addition to providing for heat recovery, LHTES performs an extremely active function in controlling the emissions from an internal combustion engine. Peak formation of criteria pollutants, which in particular include NO_x and SO_2 , occurs at "cold starts," meaning when the catalysts have not yet attained their required temperature [2, 25]. New studies reveal that using LHTES can help in controlling emission in a more direct way by employing it as "thermal batteries" [16]. During the regular functioning of the system, it stores high-grade heat and subsequently releases it so that before the next start-up of the engine, the engine's cooling fluid, the lubrication oil, or the exhaust system can be pre-heated.

VI. SCOPE AND INTEGRATION IN THE INDIAN CONTEXT

The unique conditions of energy usage in India, such as intense industrialization and the strong shift towards decarbonization coupled with heavy decentralization in power supply, open up vast opportunities for integrating the proposed TES system [17].

Commercial Infrastructures and Smart Cities: With the fast development of IT parks, the number of large diesel generator sets serving as backup power supplies remains high. By applying the TES system described in Section 4, exhaust heat can be collected to provide support to HVAC systems in compliance with ECBC standards.

Regulations and Financial Incentives: The enforcement of BS-VI emission norms by the Government of India requires highly efficient exhaust heat after-treatment. Additionally, PAT provides financial incentives for companies to implement waste heat recovery plants to generate energy-saving certificates.

6.1. Theoretical Implementation Case Study: Decentralized Agricultural Pumping

To show the practical benefits of LHTES in India, let's look at the common 10 HP (7.5 kW) stationary diesel engine used for agricultural irrigation in central India's farming areas. This engine typically runs at a thermal efficiency of 30%. It releases around 7.5 kW of continuous thermal energy into the atmosphere through exhaust gases at temperatures over 300°C.

A localized shell-and-tube LHTES unit that uses a medium-temperature, low-cost organic PCM can capture about 40% of this exhaust energy. During a standard 6-hour irrigation cycle, the LHTES unit acts as a thermal reservoir. After operation, this stored latent heat can support secondary agricultural processes that usually require burning extra biomass. It can be used for controlled crop drying, which is important for cash crops like soybeans and spices, or for pre-heating water in decentralized dairy operations without needing extra fuel.

6.2. Theoretical Implementation Case Study: Industrial Manufacturing and HVAC Support

Consider a medium-to-large manufacturing facility in central India's industrial areas, such as Pithampur. These facilities often depend on high-capacity (e.g., 500 kVA) backup diesel generator (DG) sets to keep running during power outages. A 500 kVA DG set at full load releases large amounts of thermal energy through its exhaust, often at temperatures over 400°C.

By retrofitting the exhaust manifold with a scaled shell-and-tube LHTES unit that uses a high-temperature inorganic or composite PCM, the facility can capture a significant amount of this wasted energy. When grid power is restored and the DG set is shut down, this stored thermal energy can be used to power a thermally activated Vapor Absorption Machine (VAM). The VAM can help the facility's centralized HVAC system, providing localized cooling for control rooms without taking extra electrical power from the grid. Alternatively, the heat can be used to pre-heat boiler feed water for ongoing manufacturing processes, leading to direct cost savings.

VII. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

Latent heat thermal energy storage systems have been shown to be a viable thermodynamic and environmentally important technology that can recover waste heat from combustion engines that would otherwise be dissipated via combustion exhausts. While scientists have developed sufficient empirical and scientific knowledge on phase change materials (PCMs) and thermal, steady-state modelling calorimetry methodology to evaluate PCMs, this review revealed several significant gaps in the literature that future research needs to address.

1. **Holistic Dynamic Optimization:** Very few studies exist on the simultaneous computational fluid dynamics (CFD) geometric optimization of transient fluid dynamics models and the dynamic exergy analysis (DEA) of PCMs under powering loads.
2. **Real-Time Emissions Correlation:** Future field experiments should include the embedding of sensors that provide empirical measurements of the correlation between the charge cycles of latent heat thermal energy storage (LHTES) systems and the instantaneous reduction of SO₂ and NO_x emissions.
3. **Indigenous Material Development:** To encourage widespread adoption of LHTES technology in developing economies, materials research should concentrate on developing low-cost, bio-based PCM esters or PCMs derived from industrial by-products that can provide superior stability at low cost, therefore eradicating reliance on the very expensive, highly refined, synthetic waxes that are currently being used in LHTES systems.

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