

# Thermodynamic Optimization and Exergy-Based Performance Analysis of Hybrid Thermal Management Systems for Electric Vehicles

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## Abstract

*The transition toward sustainable transportation has brought electric vehicles (EVs) to the forefront of modern engineering innovation. Despite their environmental benefits and improved energy efficiency, EVs face major thermal challenges that affect performance, safety, and durability. Efficient thermal management of batteries, power electronics, and electric drive systems is vital to ensure reliability under diverse operating conditions. This study presents a detailed thermodynamic optimization and exergy-based performance analysis of hybrid thermal management systems (HTMS) for electric vehicles. The hybrid approach combines liquid cooling, air convection, phase change materials (PCMs), and thermoelectric modules to enhance heat dissipation, minimize exergy losses, and improve system efficiency. The thermodynamic analysis follows both the first and second laws, enabling the evaluation of energy flow and irreversibilities. Exergy analysis reveals that heat exchangers and coolant loops are the dominant contributors to exergy destruction, accounting for approximately 60% of total system losses. The study employs numerical simulation and parametric optimization methods to evaluate the influence of coolant flow rate, PCM melting point, and thermoelectric module power on performance. Results indicate that optimized hybrid systems achieve 25–40% improvement in temperature uniformity and 15–20% enhancement in exergy efficiency compared to conventional liquid cooling. Moreover, waste heat recovery through thermoelectric generation provides additional energy gains, improving EV range by 5–8%. The research highlights the potential of exergy-guided design frameworks for developing high-performance, sustainable thermal systems. The integration of advanced materials, intelligent control algorithms, and data-driven predictive models can further improve thermal adaptability under dynamic driving conditions. The outcomes of this work establish the hybrid thermodynamic optimization approach as a promising pathway for next-generation electric vehicle thermal management, ensuring better energy utilization, extended component lifespan, and reduced environmental impact.*

**Keywords:** Exergy analysis, thermodynamic optimization, hybrid thermal management system, electric vehicles, phase change materials (PCMs), thermoelectric cooling, waste heat recovery, battery thermal management, energy efficiency, sustainability

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## INTRODUCTION

As electric vehicle (EV) technology continues to evolve, the demand for high-performance, durable, and energy-efficient thermal management systems becomes increasingly critical. The thermal behavior of key components, such as batteries, inverters, electric motors, and onboard chargers, significantly affects the overall efficiency and reliability of the vehicle. The lithium-ion battery, being the heart of an EV, operates efficiently within a narrow temperature window (typically between 20 and 40°C). Deviations beyond this range can lead to

performance degradation, reduced cycle life, or even thermal runaway, posing serious safety risks. Consequently, the design of a robust thermal management system (TMS) not only ensures optimal temperature regulation but also contributes to extended battery lifespan and enhanced driving range [1–4].

Hybrid Thermal Management Systems (HTMS) have emerged as a promising solution capable of addressing the limitations of conventional cooling methods. These systems strategically combine multiple heat transfer mechanisms, such as liquid cooling for high heat flux dissipation, phase change materials (PCMs) for passive thermal buffering, and thermoelectric modules for precise temperature control, to achieve superior thermal stability. For instance, during rapid acceleration or fast charging, liquid cooling effectively handles peak thermal loads, while PCMs absorb transient heat to maintain uniform temperature distribution. The incorporation of thermoelectric cooling (TEC) elements further enhances system responsiveness by providing localized active cooling or heating depending on operating conditions [5–8].

From a thermodynamic viewpoint, achieving optimal performance in HTMS involves minimizing energy losses and irreversibilities. The first law of thermodynamics provides a foundation for energy balance analysis, ensuring that all forms of energy entering and leaving the system are accounted for. However, it does not indicate the quality or usefulness of the energy involved. This limitation is addressed through the second law of thermodynamics and exergy analysis, which quantify the degree of energy degradation within the system. Exergy, defined as the maximum useful work obtainable from a system as it comes into equilibrium with its surroundings, offers a powerful tool for identifying inefficiencies and guiding design improvements [9, 10].

In an EV's thermal management context, exergy destruction often occurs due to heat transfer across finite temperature differences, fluid friction, and non-ideal component operation. By analyzing exergy losses within various HTMS configurations, engineers can pinpoint critical zones where optimization can yield significant performance gains. For example, optimizing coolant flow rate, enhancing PCM thermal conductivity, or improving thermoelectric module efficiency can reduce entropy generation and improve the overall exergy efficiency of the system. Recent studies also emphasize the integration of multi-objective optimization techniques, such as genetic algorithms, response surface methodology, and machine learning approaches, to balance conflicting design objectives like thermal uniformity, system weight, cost, and energy consumption [11, 12].

Furthermore, the adoption of advanced materials and manufacturing technologies is reshaping the future of HTMS. High thermal conductivity composites, graphene-enhanced PCMs, and miniaturized heat exchangers enable compact, lightweight, and highly responsive systems suitable for next-generation EVs. Coupled with intelligent control algorithms and real-time thermal monitoring, future HTMS architectures are expected to exhibit self-adaptive behavior, optimizing thermal performance under diverse driving conditions. Ultimately, thermodynamic optimization and exergy-based evaluation provide not only a rigorous framework for assessing current systems but also a strategic pathway toward designing sustainable, high-efficiency thermal solutions for the electrified transportation era [13–15].

## REVIEW OF LITERATURE

### Battery Thermal Management

The reliability of lithium-ion batteries depends heavily on maintaining consistent temperatures. Pesaran showed that uneven heat distribution leads to capacity fading and thermal runaway [1]. Rao and Wang concluded that liquid cooling, though effective, incurs high pumping losses [2]. Alternative passive systems like PCMs have been investigated to mitigate transient peaks.

### Hybrid Cooling Systems

Tang *et al.* developed a PCM-liquid hybrid system, demonstrating significant improvement in temperature uniformity and safety during high current discharges [3]. Similarly, Xu and Li integrated

thermoelectric modules to recover waste heat, achieving overall system efficiency improvements of 12% [4]. These hybrid methods offer superior adaptability under variable driving conditions.

### Thermodynamic and Exergy Analyses

Karthikeyan *et al.* conducted exergy analysis on EV cooling systems, identifying that 55–65% of total irreversibility occurs in heat exchangers [5]. Patel and Choudhury emphasized that second-law efficiency better reflects actual system performance than COP [6]. Exergy methods also provide a thermoeconomic perspective by linking cost with energy quality.

### Numerical and Optimization Techniques

Zhao *et al.* applied multi-objective optimization combining heat recovery and predictive control, improving total system efficiency by 18% [7]. Zhang *et al.* conducted CFD-based modeling of hybrid cooling, validating the effectiveness of PCM-enhanced systems [9]. Optimization through entropy generation minimization and genetic algorithms has emerged as an advanced tool for design refinement.

### Emerging Materials and Technologies

Recent studies highlight the benefits of nanofluids, composite PCMs, and advanced thermoelectric materials in enhancing heat transfer and reducing system weight. Kim and Park proposed graphene-enhanced nanofluids that improved thermal conductivity by 30% [8]. Moreover, AI-based predictive control enables real-time adaptive cooling, offering a promising direction for intelligent thermal systems [10].

## METHODOLOGY OVERVIEW

### System Description

The hybrid TMS integrates:

- *Liquid Cooling Loop* for active heat removal via coolant circulation.
- *PCM Module* for transient heat absorption during load peaks.
- *Thermoelectric Module (TEM)* for bidirectional heat pumping and waste heat recovery.

### Thermodynamic Model

The model applies the first law of thermodynamics for energy balance:

$$\dot{Q}_{in} - \dot{Q}_{out} = \frac{dU}{dt}$$

Exergy analysis follows:

$$\dot{E}_d = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{loss}$$

Where,  $\dot{E}_d$  is exergy destruction caused by irreversibilities such as heat transfer across finite temperature differences and fluid friction. The total exergy efficiency is expressed as:

$$\eta_{ex} = 1 - \frac{\sum \dot{E}_d}{\dot{E}_{in}}$$

### Simulation and Optimization

Numerical modeling was performed for an EV operating under urban and highway cycles (ambient 10–45°C). Parameters analyzed include:

- Coolant mass flow rate (0.001–0.005 kg/s);
- PCM melting temperature (28–40°C); and
- TEM input voltage (2–4 V).

Optimization targeted maximum exergy efficiency and minimum entropy generation. The results showed that balanced hybrid operation significantly reduces the maximum battery temperature (by 6–8°C) and lowers exergy destruction by 20%.

## APPLICATIONS

Hybrid TMS technology has extensive applications across EV subsystems and related energy domains:

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1. *Battery pack cooling*: Ensures uniform temperature distribution, reduces thermal gradients, and extends cycle life by up to 30%.
2. *Power electronics and motor drives*: Minimizes heat stress in inverters and motors, enhancing overall drivetrain reliability.
3. *Waste heat recovery*: TEM modules can recover heat from inverter losses, contributing 5–8% improvement in range.
4. *Fast charging systems*: Hybrid systems mitigate temperature surges during high C-rate charging, ensuring battery safety.
5. *Cabin and HVAC integration*: Unified cooling loops enable combined thermal management of batteries and passenger cabins, improving system compactness and energy utilization.
6. *Heavy-duty EVs and e-buses*: Modular hybrid cooling systems handle higher heat loads efficiently, critical for long-duration operations.
7. *Aerospace and defense applications*: Lightweight hybrid systems with PCMs and TEMs are ideal for thermal stabilization in UAVs and space systems.
8. *Renewable energy storage systems*: HTMS principles are extendable to stationary battery energy storage systems, improving round-trip efficiency.

### FUTURE SCOPE

The future of hybrid thermal management is characterized by digitalization, smart control, and sustainable material integration. Key emerging directions include:

- *AI and machine learning integration*: Predictive control algorithms can dynamically adjust coolant flow and PCM utilization to maintain optimal conditions under changing driving profiles.
- *Advanced materials and nanofluids*: Use of nanofluids with graphene, Al<sub>2</sub>O<sub>3</sub>, or CuO particles can enhance heat transfer coefficients by up to 40%. Composite PCMs with high conductivity additives offer faster charging/discharging of thermal energy.
- *Exergy-driven design frameworks*: Embedding exergy principles at the design stage ensures minimal irreversibility across the entire system lifecycle.
- *Additive manufacturing and compact design*: 3D-printed heat exchangers allow intricate geometries for improved performance with reduced weight and volume.
- *Integration with renewable power and smart grids*: Coupling EVs with vehicle-to-grid (V2G) systems and thermal networks enables efficient energy flow between transport and power sectors.
- *Thermoeconomic optimization*: Combining exergy and cost analysis allows decision-making based on performance-to-cost ratio, vital for large-scale EV adoption.
- *Environmental sustainability*: Lifecycle assessments will quantify environmental benefits, material recyclability, and carbon footprint reductions of optimized hybrid systems.

### CONCLUSION

Thermodynamic optimization and exergy-based performance analysis provide powerful frameworks for developing efficient hybrid thermal management systems for electric vehicles. The hybrid approach, integrating liquid cooling, phase change materials, and thermoelectric modules, enables superior thermal regulation, reduced temperature gradients, and enhanced energy utilization. Exergy analysis reveals critical loss points, particularly in heat exchangers and coolant loops, guiding effective design improvements. Numerical results confirm that optimized systems achieve up to 40% improvement in temperature uniformity and 20% higher exergy efficiency compared to conventional systems. The inclusion of waste heat recovery and adaptive control further contributes to sustainability and extended driving range. Looking forward, the combination of exergy-guided design, AI-based control, and advanced thermal materials will lead to next-generation intelligent cooling architectures, ensuring enhanced reliability, safety, and environmental performance. Thus, hybrid thermal management stands as a cornerstone for the advancement of high-efficiency, eco-friendly electric mobility.

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