JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Thermoelectric Cooling-Based Thermal Management in $LiFePO_4$ Batteries for Compact EV Applications

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Abstract: Efficient thermal regulation is critical for maintaining the performance and safety of lithium-ion batteries, especially under high current scenarios such as fast charging and discharging. This study presents the design and experimental evaluation of a hybrid Battery Thermal Management System (BTMS) based on a Thermoelectric Cooler (TEC) integrated with a water-cooled heat sink. A prismatic lithium iron phosphate ($LiFePO_4$) battery cell was tested under four scenarios, with and without active cooling. Results showed that the TEC-based system significantly reduced peak surface temperatures by over 18%, improved voltage stability by 5.5%, extended discharge time by 15 %, these findings highlight the system's suitability for compact electric vehicles (2- and 3-wheelers), offering a low-cost, scalable, and reliable solution for battery thermal management.

Key Words- **Thermoelectric Cooling (TEC), Battery Thermal Management System (BTMS), $LiFePO_4$ Prismatic Cell**

I. Introduction

1.1 Importance of Thermal Management in Li-ion Batteries

Lithium-ion batteries are widely used in electric vehicles (EVs) due to their high energy density and long cycle life. However, during fast charging and discharging, internal heat generation can degrade performance, accelerate aging, and pose safety risks such as thermal runaway. Maintaining optimal temperature (typically 20–40°C for $LiFePO_4$) is essential for battery reliability.

1.2 EV Battery Configuration:

- Cell: Basic energy storage unit (anode, cathode, electrolyte, separator).
- Module: Multiple cells connected for desired voltage and capacity.
- Pack: Modules integrated with Battery Management Systems (BMS), thermal management, and safety features.
- System: Complete integration with vehicle platform, powertrain, and control systems.

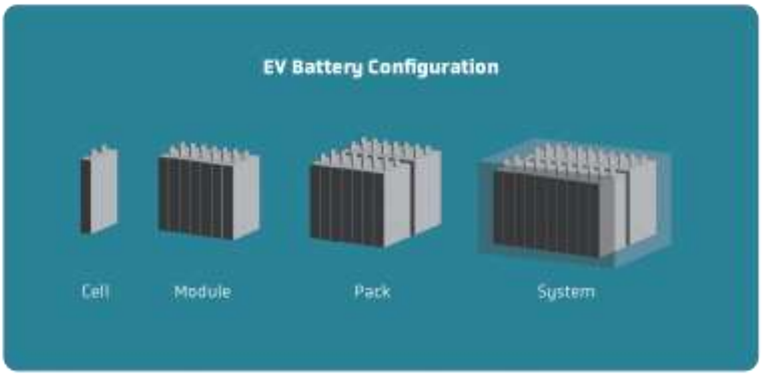

Figure 1: EV Battery Configuration

1.3 FAST CHARGING/DISCHARGING THERMAL CHALLENGES

Fast charging or discharging introduces severe thermal loads due to internal resistance and Joule heating. This leads to:

- Temperature rise beyond 37°C
- Non-uniform heat distribution
- Risk of capacity fade and voltage sag
- Potential thermal runaway

1.4 $LiFePO_4$ FOR EVS AND ITS LIMITATIONS

$LiFePO_4$ cells are thermally stable and safer than other chemistries. However, even these cells experience significant heating under fast load conditions, especially in compact vehicle platforms where airflow is limited.

1.5 Thermoelectric Cooling (TEC) as a Solution

TEC systems based on the Peltier effect offer compact, solid-state cooling. When combined with aluminum heat spreaders and water-cooled heat sinks, they enable:

- Precise temperature control
- Compact installation
- Enhanced battery safety

1.6 PELTIER EFFECT

Observed in 1834, it describes the heat absorption and release that occurs at the junctions of two dissimilar materials when electric current flows through them. Heat is absorbed at one side (cold side) and released at the other (hot side), enabling solid-state cooling.

II. LITERATURE REVIEW

[1] Di, Luo, and Ye (2024) This study proposed a hybrid TEC-based BTMS integrating air and water cooling. Using a multiphysics simulation, researchers evaluated the effect of TEC current, water, and airflow rates on system efficiency. Results confirmed that TEC-based BTMS provides enhanced thermal regulation across operational modes, supporting battery reliability under varying thermal loads, especially during high-performance EV applications.

[2] Di, Luo, Zihao, Wu, and Jin (2023) Researchers developed a finned hybrid BTMS using TECs and PCMs. A transient multiphysics model revealed that optimizing TEC input current and fin geometry greatly reduced battery temperature and PCM melting fraction. This hybrid design improved cooling response, offering higher reliability in temperature-sensitive applications, particularly in fast-charging and high-discharge operations.

[3] Di, Luo, and Haifeng Wu (2023) This research presented a vapor chamber–TEC hybrid BTMS to enhance battery temperature control. Numerical simulations showed the system could maintain thermal uniformity and lower peak temperatures. By adjusting TEC parameters, the BTMS significantly improved heat dissipation, extending battery life and stability, making it ideal for energy-dense applications like electric mobility and high-capacity storage systems.

[4] Hamed, Khalili, Pouria (2022) This study investigated a compact nanofluid-TEC hybrid BTMS using Peltier devices. It focused on maintaining battery temperatures below 25°C while minimizing lithium-ion loss and energy fade. Results demonstrated efficient thermal regulation with low energy usage. The use of nanofluids enhanced heat transfer, and the system design showed potential for integration into portable or compact EV battery packs.

[15] Zare and Perera (2025) Zare and Perera introduced a PCM-based BTMS with both internal and external fins to address PCM’s low thermal conductivity. Using lumped modeling and enthalpy-porosity analysis, the system showed reduced surface temperature variation by 15.98 K and improved cooling recovery by 37.56% at 5C. This hybrid approach improved phase-change stability and temperature uniformity, making it suitable for high-rate charging applications in electric vehicles.

[16] Saber et al. (2025) Saber et al. reviewed various BTMS strategies for prismatic Li-ion batteries, focusing on performance under high load. Liquid cooling dominated real-world applications (≈80%) for its reliability, while PCM and hybrid systems gained attention for better control. However, PCM’s low conductivity and hybrid complexity remain challenges. The review highlights the urgent need for scalable, efficient BTMS to enhance battery safety, life, and thermal balance.

[17] Tai et al. (2024) Tai et al. analyzed fast-charging scenarios and cooling strategies for Li-ion batteries. The study identified rapid thermal buildup as a major concern and reviewed indirect liquid, immersion, and hybrid systems from 2019–2024.

Although hybrid systems showed superior thermal control, they were found to be structurally complex. The study confirms the critical role of advanced BTMS in enabling safe, high-performance EV battery operation.

2.1 Existing BTMS Methods

Battery Thermal Management Systems (BTMS) are critical in preserving the performance, safety, and longevity of lithium-ion batteries, particularly under high charge-discharge rates. Several BTMS methods have been studied extensively:

- Air Cooling: Low cost but ineffective under high loads.
- Liquid Cooling: Efficient but complex and bulky.
- Phase Change Materials (PCMs): Compact but slow to recharge.
- Heat Pipes: Effective but not ideal for densely packed cells.

Each method has trade-offs between efficiency, complexity, scalability, and cost, especially for small-format or prismatic batteries used in compact electric vehicles (EVs).

2.2 TEC in Literature

Several simulation-based studies show TEC potential for battery cooling. However, very few studies provide:

- Real-time, fast-charging scenarios
- Practical, single-cell testing
- Comparative data on temperature, SOC, and voltage

2.3 RESEARCH GAP & OBJECTIVE

There is limited experimental validation of TEC-water hybrid cooling systems in real-world fast charge-discharge cycles, especially on $LiFePO_4$ prismatic cells used in 2- and 3-wheelers. This study aims to bridge that gap.

III. System Design and Methodology

3.1 Experimental Setup

The developed thermal management system consists of a Thermoelectric Cooler integrated with a water-cooled heat sink and forced air radiator. This hybrid setup is designed to manage the heat generated during rapid charging and discharging of $LiFePO_4$ prismatic cells.

- Battery Cell: A single $LiFePO_4$ prismatic cell was used as the experimental unit due to its thermal stability and wide use in EVs.
- TEC Module: A thermoelectric cooler was placed directly in contact with the battery surface using thermal paste to enhance heat transfer.
- Aluminum Heat Spreader: Positioned between the TEC and battery for uniform thermal conduction.
- Water-Cooled Heat Sink: Attached to the hot side of the TEC to dissipate extracted heat.
- Forced Air Radiator & Pump: Ensures continuous coolant circulation and airflow, enhancing heat removal capacity.
- Sensors: Temperature (T1, T2), voltage, current, and SOC were logged using digital instruments at 2-minute intervals.

3.2 Working Principle

- The TEC module actively absorbs heat from the battery's surface (cold side) and transfers it to the hot side.
- The heat is then conducted to the water-cooled heat sink, where the coolant absorbs and carries it away.
- A radiator and fan further remove heat from the circulating fluid.
- This dual-action system prevents overheating during high-load conditions and ensures uniform temperature distribution, crucial for safety and performance.

3.3 Test Scenarios

- Fast charging without cooling
- Fast discharging without cooling
- Fast charging with TEC-based cooling
- Fast discharging with TEC-based cooling

IV Results and Discussion

4.1 Temperature Regulation: TEC-based system reduced charging temperature from 37.6℃ to 29.6℃
Discharge temperatures remained under 32℃ compared to 32.6℃–37.6℃ in non-cooled runs.

4.2 SOC and Charging Time: Charging time reduced by 10%
Discharge duration extended by 15 %, indicating better energy retention.

4.3 Voltage Stability: Voltage drop during discharge reduced by 5.5%, from 0.92 V to 0.86 V, due to lower internal resistance.

4.4 Temperature Uniformity: The temperature difference between T1 and T2 was reduced from 1.2℃ to 0.3℃ showing uniform heat dissipation and less thermal stress.

4.5 Practical Implication: This modular, low-power cooling system is ideal for compact electric 2- and 3-wheelers, especially in thermally challenging environments.

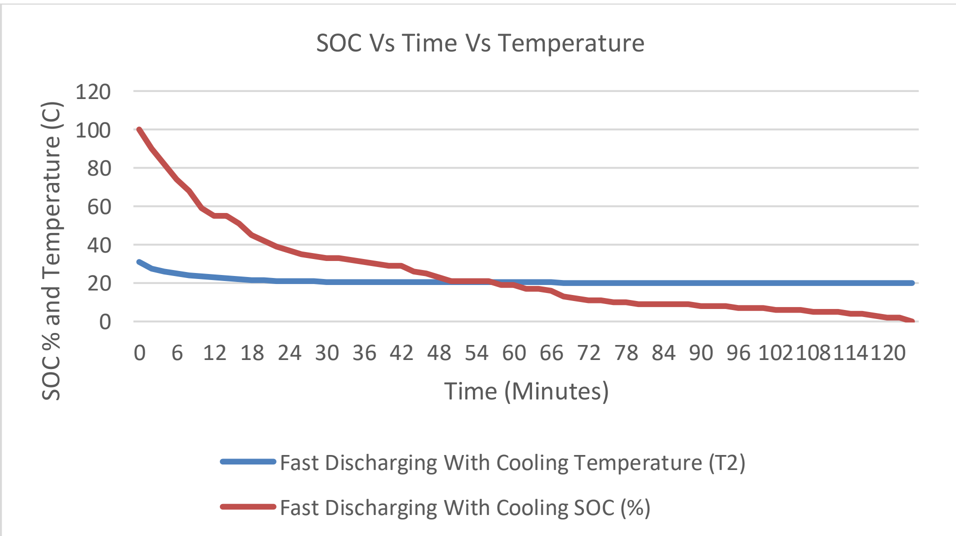

Figure 2: Fast Discharging With Cooling

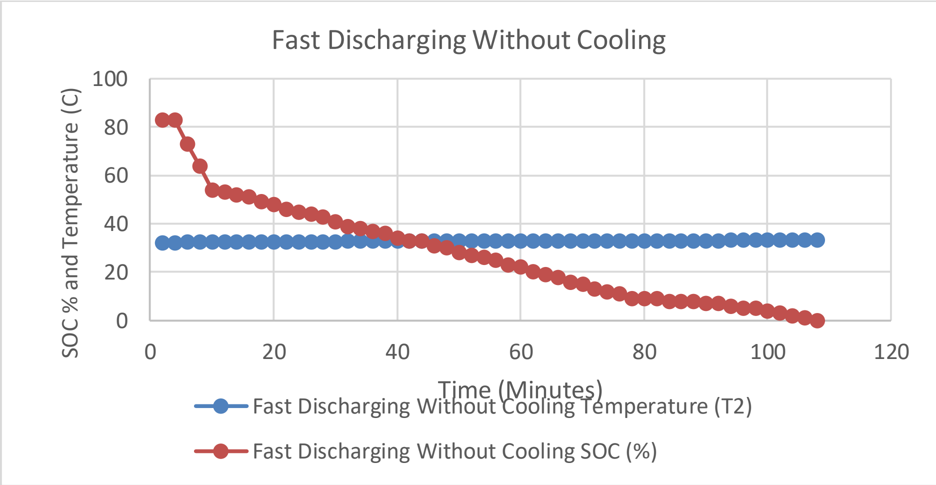

Figure 3: Fast Discharging without Cooling

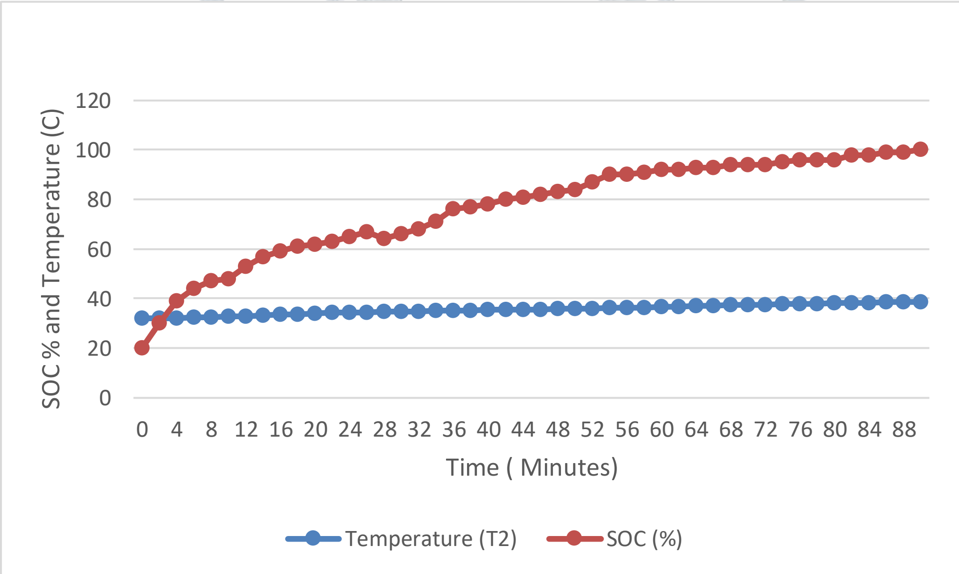

Figure 4: Fast charging without Cooling

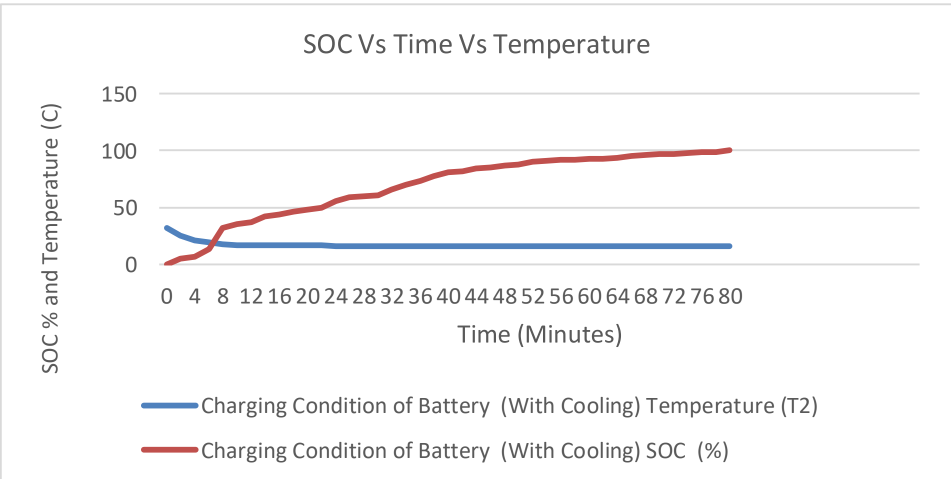

Figure 5: Fast Charging with Cooling

Table No: 1.1 Comparative analysis with and without TEC-based cooling

Parameter	Without Cooling	With TEC-Based Cooling
Peak Temp (T1/T2)	32.6–37.6 °C	19.0–25.9 °C
SOC Rise (Charging)	Fast, high heat buildup	Smooth, lower temps
SOC Drop (Discharging)	Abrupt, unstable	Gradual, thermally stable
Voltage Drop	Significant	Controlled and minimized
Thermal Stability	Poor, uneven distribution	Excellent, uniform profile

V Conclusion

This study confirms the effectiveness of a TEC-integrated hybrid cooling system for managing thermal stress in $LiFePO_4$ prismatic battery cells under fast charging and discharging conditions. The system:

- Reduces peak and average temperatures, maintaining safe operating conditions.
- Improves charging speed by ~10% and discharge runtime by ~15%.
- Enhances voltage stability and thermal uniformity, reducing the risk of thermal runaway.
- Demonstrates scalability and simplicity, making it suitable for real-world EV applications.

Such a system is especially valuable for low-cost, compact electric vehicles operating in thermally constrained environments.

VI Future Scope

- Integration with smart Battery Management Systems (BMS)
- Scaling to multi-cell modules and packs
- Optimization of TEC placement and materials
- Field testing in real vehicles under varied climatic conditions

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