iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VIII **Month of publication:** August 2026

DOI: https://doi.org/10.22214/ijraset.2026.84694

Review on Thermal Management System of Electric Vehicles

Mr. Akshay B. Akhade
Department of Electrical Engineering, Vidya Pratishthan's Kamalnayan Bajaj Institute of Engineering and Technology (VPKBIET), Baramati

***Abstract:** The rapid growth of electric vehicles (EVs) has transformed the transportation sector by reducing dependence on fossil fuels and minimizing greenhouse gas emissions. However, the reliability, safety, and efficiency of EVs strongly depend on effective thermal management. Electric vehicle subsystems such as lithium-ion batteries, electric motors, power electronic converters, and charging systems generate substantial heat during operation. Excessive temperature rise can lead to reduced efficiency, accelerated degradation, lower driving range, and severe safety concerns including thermal runaway. Therefore, a robust Thermal Management System (TMS) is essential to maintain optimal operating conditions.*

This paper presents a detailed review of thermal management systems used in electric vehicles with emphasis on battery thermal regulation, cooling technologies, and intelligent thermal control strategies. Various cooling approaches including air cooling, liquid cooling, refrigerant cooling, phase change materials (PCM), heat pipes, and nanofluid-based cooling are critically analyzed. The paper also discusses thermal modeling techniques, computational fluid dynamics (CFD) simulations, and experimental investigations carried out for EV battery packs and associated subsystems. Comparative analysis shows that liquid cooling systems provide superior heat dissipation, whereas hybrid systems integrating PCM and nanofluids offer improved thermal stability and energy efficiency.

Additionally, the study highlights major challenges such as cost, system complexity, packaging constraints, coolant leakage, and environmental considerations. Emerging technologies including artificial intelligence-based predictive cooling, smart sensors, digital twins, and eco-friendly cooling materials are explored as future directions. The paper concludes that advanced and integrated thermal management systems are fundamental for improving EV safety, extending battery lifespan, enhancing vehicle performance, and supporting sustainable transportation.

***Keywords:** Electric Vehicles, Thermal Management System, Battery Cooling, Lithium-Ion Battery, Liquid Cooling, Phase Change Materials, Nanofluids, Energy Efficiency, Thermal Runaway, Electric Mobility.*

I. INTRODUCTION

The transportation industry is currently experiencing a major transformation due to increasing environmental concerns, depletion of fossil fuel reserves, and strict emission regulations imposed by governments worldwide. Electric vehicles (EVs) have emerged as one of the most promising solutions for achieving sustainable transportation because they offer high efficiency, low operating cost, and reduced environmental impact compared to conventional internal combustion engine vehicles.

The core components of electric vehicles include lithium-ion battery packs, electric motors, inverters, converters, onboard chargers, and power electronic systems. These components generate significant heat during charging and discharging processes, especially under high load and fast charging conditions. Unlike conventional vehicles where engine waste heat can be tolerated to some extent, EV components operate within narrow temperature ranges. Even slight temperature variations can affect battery capacity, charging speed, efficiency, and system reliability.

Among all EV subsystems, the battery pack is the most temperature-sensitive component. Lithium-ion batteries generally perform efficiently within a temperature range of 20°C to 40°C. Operation beyond this range may result in reduced battery performance, rapid aging, electrolyte degradation, and thermal runaway. Similarly, electric motors and power electronic devices experience increased switching losses and reduced efficiency at elevated temperatures.

Thermal management systems are therefore designed to regulate temperature distribution, remove excess heat, and maintain thermal uniformity within EV subsystems. A properly designed TMS improves safety, extends component lifespan, increases driving range, and enhances passenger comfort. With the growing demand for high-performance EVs and ultra-fast charging systems, thermal management has become one of the most important research areas in electric mobility.

This paper provides an extensive overview of thermal management systems used in EVs. It discusses heat generation mechanisms, thermal modeling techniques, cooling methods, experimental analysis, challenges, and future research trends. The paper aims to provide researchers, engineers, and students with a comprehensive understanding of thermal management technologies and their role in modern electric vehicles.

II. IMPORTANCE OF THERMAL MANAGEMENT IN ELECTRIC VEHICLES

Thermal management plays a vital role in maintaining the efficiency, reliability, and safety of electric vehicles. The increasing power density of EV components and the demand for fast charging have made heat control more challenging than ever before.

A. Battery Safety

Lithium-ion batteries are highly sensitive to temperature fluctuations. Excessive heat generation may lead to thermal runaway, which is a dangerous condition where uncontrolled temperature rise causes fire or explosion. Effective cooling systems reduce this risk and ensure safe operation.

B. Performance Enhancement

Battery performance directly depends on operating temperature. At low temperatures, battery internal resistance increases, reducing power delivery and driving range. At high temperatures, battery degradation accelerates. Thermal management maintains batteries within the optimum temperature range for efficient performance.

C. Longer Battery Life

Frequent exposure to elevated temperatures accelerates chemical degradation inside battery cells. By maintaining uniform temperatures, thermal management systems minimize aging effects and improve battery cycle life.

D. Improved Charging Efficiency

Fast charging generates substantial heat due to high current flow. Efficient thermal regulation allows faster charging without damaging the battery pack.

E. Passenger Comfort

Modern EVs integrate cabin thermal systems with battery cooling systems. Efficient heat management ensures passenger comfort while minimizing energy consumption.

F. Reliability of Power Electronics

Power electronic devices such as inverters, converters, and motor drives generate heat due to switching losses and conduction losses. Proper cooling improves reliability and prevents overheating.

III.HEAT GENERATION IN ELECTRIC VEHICLES

Heat generation in EVs occurs in multiple subsystems due to electrical, electrochemical, and mechanical losses.

A. Heat Generation in Batteries

Battery heat generation mainly occurs due to:
1) Ohmic losses caused by internal resistance.
2) Electrochemical reactions during charging and discharging.
3) Entropy changes within battery cells.
4) Side reactions occurring at high temperatures.

The heat generated in batteries can be represented as:
[Q = I^2R + IT]
Where:
- (Q) = Heat generated
- (I) = Current
- (R) = Internal resistance

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

- (T) = Temperature
- (E) = Open circuit voltage

The first term represents irreversible heat generation while the second term represents reversible heat generation.

B. Heat Generation in Electric Motors

Electric motors generate heat due to:

1) Copper losses in stator windings.
2) Iron losses in magnetic cores.
3) Mechanical friction.
4) Windage losses.

High temperatures reduce motor efficiency and insulation life.

C. Heat Generation in Power Electronics

Power semiconductor devices such as IGBTs and MOSFETs generate heat due to:

1) Switching losses.
2) Conduction losses.
3) Leakage currents.

Thermal stress affects switching performance and device reliability.

D. Heat Generation During Fast Charging

Fast charging significantly increases current flow through battery cells, resulting in higher resistive heating. Efficient thermal control is essential during rapid charging to avoid overheating.

IV. THERMAL MANAGEMENT SYSTEM ARCHITECTURE

An electric vehicle thermal management system consists of sensors, cooling circuits, heat exchangers, controllers, pumps, and cooling materials. The system continuously monitors and regulates subsystem temperatures.

A. Main Components of TMS

1) Temperature Sensors: Sensors monitor battery temperature, coolant temperature, motor temperature, and ambient conditions.
2) Cooling Unit: The cooling unit removes excess heat using air, liquid, refrigerant, or advanced cooling materials.
3) Heat Exchanger: Heat exchangers transfer heat from hot components to the surrounding environment.
4) Pumps and Fans: Pumps circulate coolant while fans improve airflow for heat dissipation.
5) Thermal Controller: Electronic controllers regulate cooling operation based on real-time temperature conditions.
6) Insulation Materials: Thermal insulation prevents heat transfer between adjacent battery cells.

V. AIR COOLING SYSTEMS

Air cooling is one of the simplest and most economical thermal management methods used in electric vehicles.

A. Working Principle

Air cooling systems use natural or forced airflow to remove heat from batteries and electronic components. Fans circulate air through cooling channels surrounding battery modules.

B. Types of Air Cooling

1) Natural Air Cooling: Heat dissipation occurs through natural convection without external fans.
2) Forced Air Cooling: Electric fans force air through battery modules to improve cooling performance.

C. Advantages

1) Simple construction.
2) Low manufacturing cost.
3) Lightweight system.
4) Minimal maintenance.

D. Limitations

1) Poor heat transfer capability.
2) Non-uniform temperature distribution.
3) Reduced effectiveness in high ambient temperatures.
4) Limited suitability for high-power EVs.

E. Applications

Air cooling is mainly used in low-cost electric vehicles and hybrid vehicles where heat generation is relatively low.

VI. LIQUID COOLING SYSTEMS

Liquid cooling is the most widely used thermal management technology in modern electric vehicles because liquids have higher thermal conductivity and heat capacity compared to air.

A. Working Principle

Coolant circulates through cooling plates or channels attached to battery modules. Heat from the battery pack transfers to the coolant and is then dissipated through a radiator or heat exchanger.

B. Types of Liquid Cooling

1) Direct Liquid Cooling: Coolant directly contacts battery surfaces for efficient heat transfer.
2) Indirect Liquid Cooling: Coolant flows through separate channels or plates adjacent to battery cells.

C. Common Coolants

1) Water-glycol mixtures.
2) Dielectric fluids.
3) Refrigerants.
4) Nanofluids.

D. Advantages

1) High heat transfer efficiency.
2) Uniform temperature distribution.
3) Suitable for fast charging applications.
4) Better thermal control for high-power EVs.

E. Disadvantages

1) High system cost.
2) Complex design.
3) Possibility of coolant leakage.
4) Increased maintenance requirements.

F. Industrial Applications

Many modern EV manufacturers including Tesla, BMW, Hyundai, and BYD use liquid cooling systems in battery packs.

VII. REFRIGERANT COOLING SYSTEMS

Refrigerant cooling systems use the vehicle air conditioning cycle to regulate battery temperature.

A. Operating Principle

Refrigerants absorb heat from the battery pack through evaporators and release it to the surroundings through condensers.

B. Advantages
1) High cooling efficiency.
2) Rapid temperature reduction.
3) Effective under extreme conditions.

C. Limitations
1) Complex integration.
2) High energy consumption.
3) Environmental concerns related to refrigerants.

D. Applications

Refrigerant cooling is often used in premium EVs and fast charging systems.

VIII. PHASE CHANGE MATERIAL (PCM) BASED COOLING

Phase change materials absorb large amounts of heat during phase transition, thereby limiting temperature rise.

A. Working Principle

PCM absorbs latent heat while changing from solid to liquid phase during battery heating.

B. Common PCM Materials
1) Paraffin wax.
2) Fatty acids.
3) Hydrated salts.

C. Advantages
1) Passive cooling.
2) No external power required.
3) Improved thermal uniformity.
4) Reduced peak temperature.

D. Limitations
1) Low thermal conductivity.
2) Leakage issues.
3) Additional system weight.

E. Hybrid PCM Systems

Researchers often combine PCM with liquid cooling or heat pipes to improve overall thermal performance.

IX. HEAT PIPE COOLING SYSTEMS

Heat pipes are passive thermal devices that transfer heat using evaporation and condensation cycles.

A. Construction

A heat pipe consists of:
1) Evaporator section.
2) Condenser section.
3) Working fluid.
4) Wick structure.

B. Working Mechanism

Heat causes fluid evaporation at the hot end. Vapor moves to the cold region where it condenses and releases heat.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

C. Advantages
1) High thermal conductivity.
2) Passive operation.
3) Lightweight design.
4) Compact structure.

D. Applications

Heat pipes are used in battery packs, power electronics, and onboard chargers.

X. NANOFLUID BASED COOLING SYSTEMS

Nanofluids are advanced coolants containing nanoparticles suspended in base fluids.

A. Types of Nanoparticles
1) Aluminum oxide (Al2O3).
2) Copper oxide (CuO).
3) Carbon nanotubes.
4) Graphene nanoparticles.

B. Advantages
1) Enhanced thermal conductivity.
2) Improved heat transfer.
3) Better cooling efficiency.

C. Challenges
1) Stability issues.
2) Corrosion concerns.
3) High production cost.
4) Sedimentation problems.

D. Research Trends

Researchers are investigating hybrid nanofluids and environmentally friendly nanoparticle materials for EV applications.

XI. BATTERY THERMAL MODELING

Thermal modeling is essential for designing efficient cooling systems and predicting battery temperature behavior.
1) Electro-Thermal Models: Electro-thermal models combine electrical and thermal characteristics to estimate heat generation.
2) Equivalent Circuit Models: These models use resistors and capacitors to represent battery dynamics.
3) Finite Element Analysis (FEA): FEA helps analyze heat distribution inside battery modules.
4) Computational Fluid Dynamics (CFD): CFD simulations evaluate coolant flow and heat transfer performance
5) Thermal Runaway Modeling: Thermal runaway models predict hazardous conditions and improve battery safety.

XII. EXPERIMENTAL SETUP AND TESTING

To evaluate thermal management performance, an experimental test bench was designed with battery modules, sensors, and cooling circuits.

A. Experimental Components
1) Lithium-ion battery pack.
2) Liquid cooling loop.
3) Temperature sensors.
4) Data acquisition system.
5) Cooling pump.
6) Heat exchanger.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

B. Testing Conditions

Experiments were conducted under:

1) Different discharge rates.
2) Fast charging conditions.
3) Variable ambient temperatures.
4) Dynamic driving cycles.

C. Measured Parameters

1) Maximum battery temperature.
2) Temperature uniformity.
3) Cooling efficiency.
4) Pressure drop.
5) Energy consumption.

XIII. RESULTS AND DISCUSSION

1) Battery Temperature Performance: Liquid cooling systems maintained battery temperature within the range of 25°C to 35°C under high load conditions. Air cooling systems showed higher temperature variations.
2) Thermal Uniformity: Hybrid PCM and liquid cooling systems achieved better thermal uniformity compared to standalone cooling systems.
3) Energy Efficiency: Advanced cooling systems reduced battery degradation and improved vehicle efficiency.
4) Fast Charging Performance: Efficient cooling enabled higher charging rates while maintaining safe operating temperatures.
5) Nanofluid Performance: Nanofluid coolants demonstrated superior heat transfer characteristics compared to conventional water-glycol mixtures.

XIV. THERMAL RUNAWAY AND SAFETY CONSIDERATIONS

Thermal runaway is one of the most critical safety issues in lithium-ion batteries.

A. Causes of Thermal Runaway

1) Overcharging.
2) Internal short circuit.
3) Mechanical damage.
4) Excessive temperature rise.

B. Effects of Thermal Runaway

1) Fire hazards.
2) Explosion risks.
3) Toxic gas release.
4) Battery destruction.

C. Prevention Techniques

1) Thermal barriers.
2) Cooling systems.
3) Battery management systems.
4) Fault detection algorithms.
5) Smart thermal sensors.

XV. BATTERY MANAGEMENT SYSTEM AND THERMAL INTEGRATION

The Battery Management System (BMS) works together with the thermal management system to ensure safe and efficient battery operation.

A. *Functions of BMS*

1) Monitoring voltage and current.
2) Estimating State of Charge (SOC).
3) Estimating State of Health (SOH).
4) Balancing battery cells.
5) Controlling cooling systems.

B. *Thermal Control Integration*

Modern BMS algorithms use real-time temperature data to optimize cooling performance and energy consumption.

XVI. INTELLIGENT THERMAL MANAGEMENT SYSTEMS

Artificial intelligence and machine learning are increasingly used in EV thermal management.

1) AI-Based Predictive Cooling: Machine learning algorithms predict temperature rise and activate cooling systems before overheating occurs.
2) Digital Twin Technology: Digital twins create virtual models of EV thermal systems for real-time monitoring and optimization.
3) Internet of Things (IoT): IoT sensors enable remote thermal monitoring and diagnostics.
4) Adaptive Cooling Control: Adaptive systems dynamically adjust cooling parameters based on driving conditions and battery state.

XVII. INTEGRATION WITH VEHICLE THERMAL SYSTEMS

Modern EVs integrate battery cooling, motor cooling, and cabin air conditioning into a unified thermal management architecture.

1) Integrated Thermal Loops: Integrated cooling loops reduce energy consumption and improve system efficiency.
2) Waste Heat Recovery: Waste heat from power electronics can be reused for cabin heating.
3) Heat Pump Systems: Heat pumps improve heating efficiency in cold climates and extend vehicle driving range.

XVIII. ENVIRONMENTAL AND SUSTAINABILITY ASPECTS

Thermal management systems must also support environmental sustainability.

1) Eco-Friendly Coolants: Researchers are developing biodegradable and non-toxic coolants.
2) Energy Conservation: Efficient thermal management reduces energy losses and improves EV efficiency.
3) Recycling and Disposal: Proper disposal of cooling materials and batteries is essential for environmental protection.

XIX. CHALLENGES IN EV THERMAL MANAGEMENT

Despite major advancements, several challenges remain in EV thermal management.

1) High Cost: Advanced cooling systems increase vehicle manufacturing costs.
2) Packaging Constraints: Compact EV designs limit available space for cooling components.
3) System Complexity: Integrated cooling systems require sophisticated control strategies.
4) Coolant Leakage: Liquid cooling systems are vulnerable to leakage and corrosion.
5) Extreme Climate Operation: Maintaining optimal battery temperature in hot and cold climates remains challenging.
6) Fast Charging Heat Generation: Ultra-fast charging creates excessive heat that requires highly efficient cooling systems.

XX. FUTURE SCOPE AND RESEARCH DIRECTIONS

Future thermal management systems are expected to become more intelligent, compact, and environmentally sustainable.

1) Artificial Intelligence Integration: AI-driven thermal control systems will optimize cooling performance and reduce energy consumption.
2) Advanced Cooling Materials: Research is focused on graphene-based materials, advanced PCM composites, and hybrid nanofluids.
3) Solid-State Batteries: Solid-state batteries may reduce thermal risks and simplify cooling requirements.
4) Smart Sensors: Next-generation sensors will enable accurate real-time temperature monitoring.
5) Vehicle-to-Grid (V2G) Integration: Thermal systems will support bidirectional charging and grid interaction.
6) Lightweight Cooling Architectures: Future EVs will use compact and lightweight thermal systems to improve efficiency.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VIII Aug 2026- Available at www.ijraset.com

XXI. CONCLUSION

Thermal management systems are indispensable for the safe, efficient, and reliable operation of electric vehicles. As electric mobility continues to expand globally, the demand for advanced thermal technologies is increasing rapidly. Batteries, motors, and power electronics generate considerable heat during operation, making effective cooling essential for maintaining performance and safety.

This paper presented a detailed study of various thermal management technologies including air cooling, liquid cooling, refrigerant cooling, phase change materials, heat pipes, and nanofluids. Comparative analysis revealed that liquid cooling systems currently offer the best overall thermal performance for high-power electric vehicles, while hybrid cooling systems combining PCM and nanofluids show promising potential for future applications.

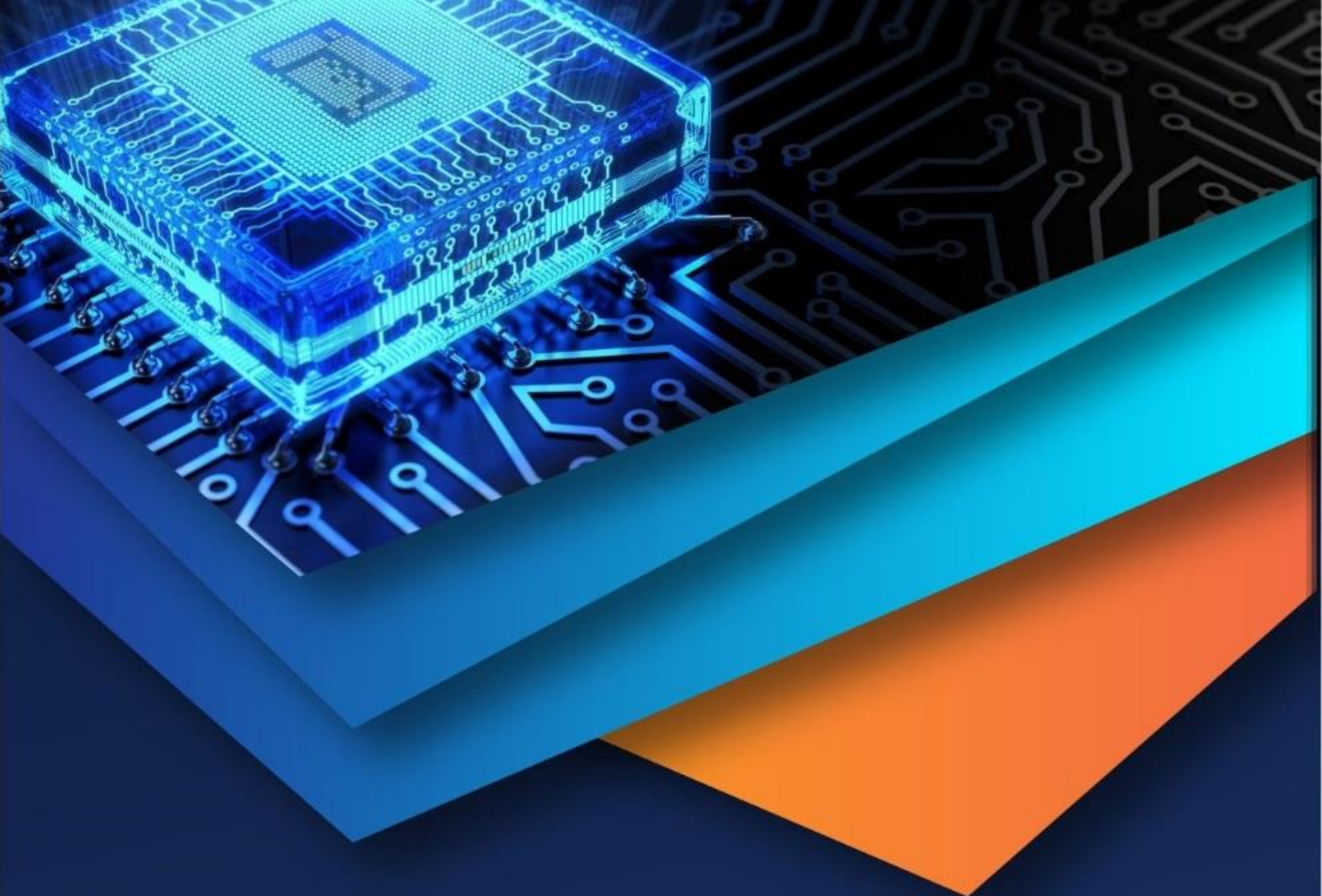
Thermal modeling, CFD analysis, and experimental investigations demonstrated the importance of maintaining temperature uniformity and preventing thermal runaway. Integration of thermal systems with battery management systems, artificial intelligence, and digital monitoring technologies is expected to significantly enhance EV reliability and efficiency.

Although challenges such as cost, complexity, packaging constraints, and environmental considerations still exist, ongoing research and technological advancements are continuously improving thermal management solutions. Future EV thermal systems will likely become intelligent, adaptive, energy-efficient, and environmentally sustainable.

Effective thermal management not only extends battery life and improves vehicle range but also ensures passenger safety and supports the global transition toward clean and sustainable transportation.

REFERENCES

[1] A. Pesaran, "Battery Thermal Management in EVs and HEVs: Issues and Solutions," SAE Technical Paper, 2002.
[2] T. M. Bandhauer, S. Garimella, and T. F. Fuller, "Thermal Issues in Lithium-Ion Batteries: A Review," Journal of the Electrochemical Society, vol. 158, no. 3, pp. R1–R25, 2011.
[3] Z. Rao and S. Wang, "A Review of Power Battery Thermal Energy Management," Renewable and Sustainable Energy Reviews, vol. 15, no. 9, pp. 4554–4571, 2011.
[4] C. Mi, M. A. Masrur, and D. W. Gao, Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives, Wiley, 2011.
[5] J. Larminie and J. Lowry, Electric Vehicle Technology Explained, Wiley, 2012.
[6] M. Ehsani, Y. Gao, and A. Emadi, Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, CRC Press, 2018.
[7] IEEE Transactions on Vehicular Technology, selected research articles on electric vehicle thermal systems.
[8] SAE International Journals on battery thermal management and EV cooling technologies.
[9] Y. Ji and C. Y. Wang, "Heating Strategies for Li-Ion Batteries Operated from Subzero Temperatures," Electrochimica Acta, vol. 107, pp. 664–674, 2013.
[10] K. Smith and C. Y. Wang, "Power and Thermal Characterization of a Lithium-Ion Battery Pack for Hybrid-Electric Vehicles," Journal of Power Sources, vol. 160, pp. 662–673, 2006.
[11] H. Khateeb, S. Amiruddin, M. Farid, J. Selman, and S. Al-Hallaj, "Design and Simulation of a Lithium-Ion Battery with a Phase Change Material Thermal Management System," Journal of Power Sources, vol. 128, pp. 292–307, 2004.
[12] X. Ling, V. Aute, and R. Radermacher, "Thermal Management Systems for Electric Vehicles," Applied Thermal Engineering, vol. 115, pp. 1169–1185, 2017.
[13] M. Javani, D. Dincer, G. F. Naterer, and B. S. Yilbas, "Heat Transfer and Thermal Management with PCMs in Electric Vehicle Battery Systems," Renewable and Sustainable Energy Reviews, vol. 52, pp. 118–132, 2015.
[14] B. Park, W. Choi, and H. Kim, "Nanofluid Cooling Technologies for EV Battery Applications," International Journal of Heat and Mass Transfer, vol. 142, 2019.
[15] International Energy Agency (IEA), Global EV Outlook Reports, recent editions.



10.22214/IJRASET

INDEX COPERNICUS
45.98

IMPACT FACTOR:
7.129

TOGETHER WE REACH THE GOAL
IMPACT FACTOR:
7.429

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY