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THERMAL MANAGEMENT IN ELECTRIC VEHICLES

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ABSTRACT

The automotive industry is undergoing a significant shift toward electric vehicles as part of efforts to control fossil fuel dependency, manage CO2 emissions, and mitigate pollution. Lithium-ion batteries, recognized for their high energy density and extended lifespan, predominantly power electric vehicles. These batteries come in various shapes such as cylindrical, prismatic, and pouch types. The operational temperature of these batteries is critical, with an optimal range of 15-35˚C for optimal performance and longevity. Deviating from this range may lead to performance degradation and potentially trigger thermal runaway.

To maintain the required battery temperature, electric vehicles employ various methods, including direct cooling, indirect cooling, and heating during cold temperatures. Indirect cooling, often combined with silicone-based materials, is a common choice among electric vehicle manufacturers due to its efficiency. In contrast, air cooling is less effective than liquid cooling, primarily due to its lower heat capacity. Phase change material (PCM) cooling, while useful, has limitations in preserving battery temperature during cold conditions, where battery capacity can drop to 60% at -40˚C compared to 100% at 20˚C. Heating during cold operating temperatures becomes essential to prevent catastrophic battery failures.

Maintaining an effective battery thermal management system is crucial to dissipate the heat generated within batteries. In instances of low-temperature operation, the incorporation of heating mechanisms becomes imperative to ensure optimal performance. This review comprehensively explores the intricacies of different cooling and heating methods employed in battery thermal management systems for electric vehicles, shedding light on the vital role these systems play in sustaining battery health and overall vehicle performance.

Keywords: Electric Vehicle, Battery, Battery Thermal Management, Direct Cooling, Indirect Cooling, Heating System.

I. INTRODUCTION

1.1 Introduction

In order to protect the environment from conventional engine emissions, most of the automotive vehicle manufacturers are working on developing alternative energy vehicles. An alternative to the conventional engines, there are battery-powered vehicle, fuel cell powered vehicle and hybrid vehicles [1]. In the battery electric vehicle, the battery powers the motor to run the wheels of the vehicle. Battery EV is a zero-emission vehicle. The hybrid electric vehicle is powered by an internal combustion engine and battery. The battery is used to store energy. These vehicles are still emitting emissions due to the internal combustion engine. Fuel cell vehicle is powered by electricity generated from the hydrogen fuel cell. This vehicle is pure emission-free and it is costlier as compared to battery electric vehicle. Therefore, out of all, battery electric vehicle is better than other vehicles considering cost and low emissions.

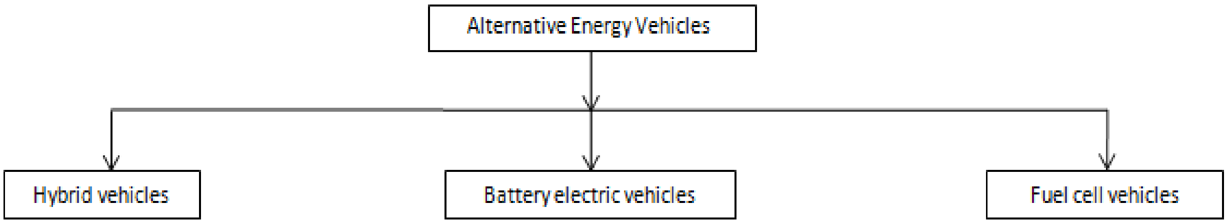

Fig. 1: Alternative energy vehicles

Battery electric vehicle consists of a battery pack, inverter, motor, transmission and thermal system [2]. Figure 2 shows the typical battery electric vehicle layout.

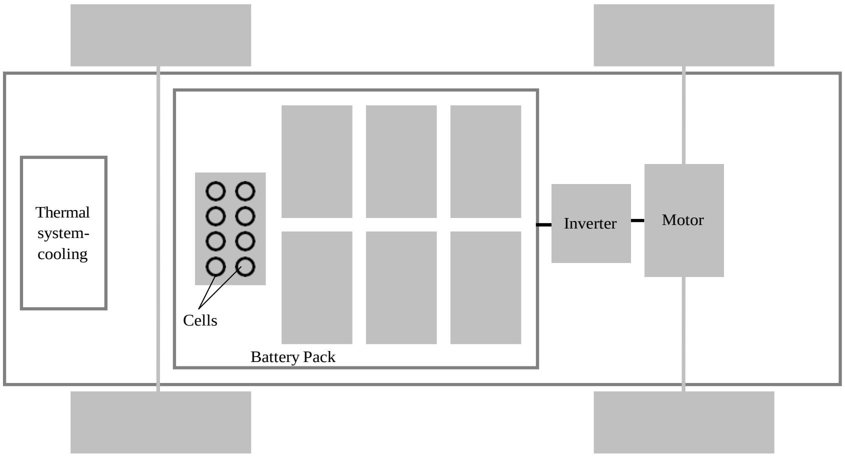

Fig. 2: Electric vehicle components

Lithium-ion batteries power most of the battery electric vehicles due to high energy density (700 Wh/L), power (10000 W/L) and long life as compared to other batteries [3]. These batteries are like a power source for many industrial applications (EV, electronic cooling and aerospace). In general, Li-ion battery consists of cathode, anode, electrolyte and separator to convert chemical energy to electrical energy. These are manufactured in cylindrical type, prismatic and pouch type shapes. Figure 3 shows the different type of batteries [4].

Fig. 3: Type of battery-Cylindrical (left), prismatic (center) and pouch (right)

Cylindrical type and pouch type batteries are widely used in passenger electric cars and commercial electric vehicles. Pros and cons of the 3 type of batteries are shown in Table 1. The available capacity of batteries in the passenger electric cars are ranging from 16 kWh to 90 kWh [5]. For the commercial vehicles, the available capacity of batteries varying from 60 kWh to 320 kWh [6]. In general, passenger EV gross weight varies from 600 kg to 2600 kg and battery pack weight varies from 100 kg to 544 kg [7]. Commercial EV gross weight varies from 12000 kg to 36000 kg and battery pack weight varies from 1300 kg to 18000 kg [6].

Table 1: Different type of batteries

Function	Cylindrical	Prismatic	Pouch
Pros	Cheap & commoditized	Best scalability; High cycle life	Form factor
Cons	Need sophisticated BMS	Currently expensive	Expensive and hard to scale
Main cell maker	Panasonic	EnerDel, ATL, PEVE, LEJ	AESE, LG Chem., SK Innovation
Market share-volume	25%	26%	49%
Market share-sales	13%	33%	54%
Main auto OEM	Tesla	Toyota, Mitsubishi, Honda, BMW, VW, Audi, Chrysler, BYD, Ford	Nissan, GM, Ford, Renault, Daimler, Hyundai, Volvo

Many numbers of batteries are packed to get more power. So, the battery pack in electric vehicle consists of any number of identical cells as shown in Fig 4. This may be configured in a series, parallel or a mixture of both to deliver the desired voltage and capacity.

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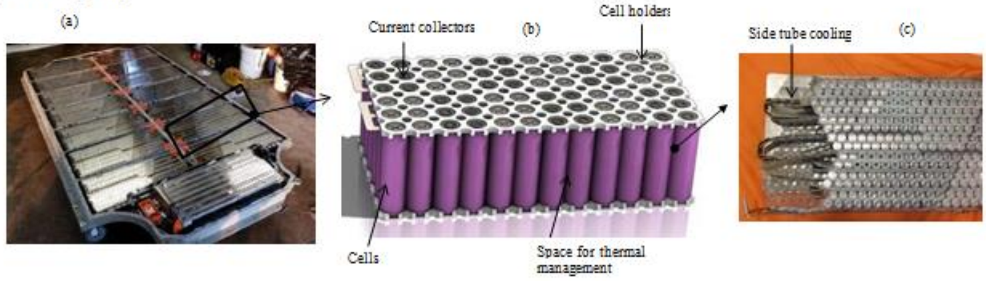


Fig. 4: (a) Battery pack (b) battery module (c) thermal management

Figure 4 shows the pouch type battery pack. Battery module consists of cylindrical type cells, cooling fin, cell foam, silicone materials and frames. Batteries are held by spacer in the module and module is mounted on the frame. Spacer and carbon or silicone-based materials absorb the vibrational loads in the battery pack [2]. Electric vehicle battery pack undergoes different discharge conditions when the vehicle is operated under different speed conditions. In general, electric vehicles were tested using WLTP (World harmonized Light vehicle Test Procedure [8]) and NEDC (New European Driving Cycle [8]) test procedures.

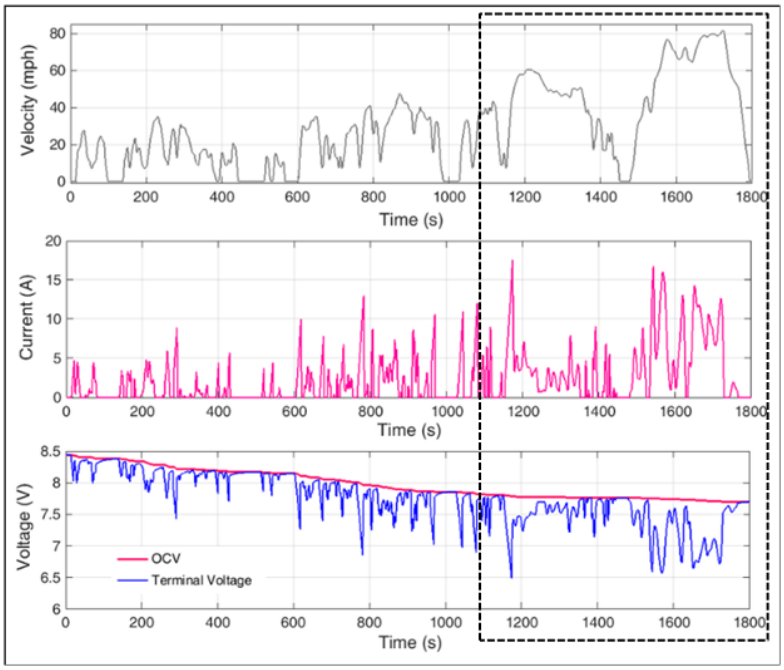


Fig. 5: WLTP cycle velocity, current and voltage

EV speed changing with time in the WLTP cycle is shown in Fig.5. The higher speed of EV requires higher current and voltage. So, this cyclic behaviour will results in higher heat generation within the battery. Heat generation of the battery with time is shown in Fig. 6.

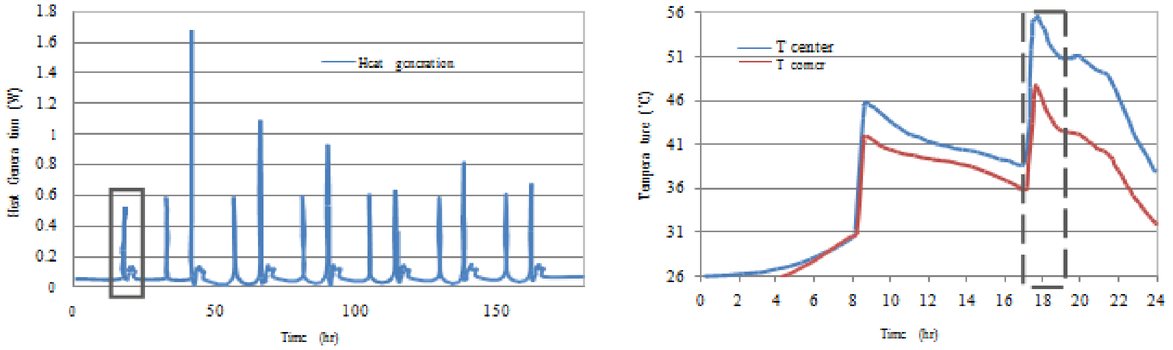


Fig. 6: Heat generation and Temperature variation with time [9]

Higher heat generation in the battery can increase the battery temperature as shown in Fig.6. Battery temperature increase with time due to continuous discharge of the battery for different EV speeds. Jaydep M. [10] studied the effect of temperature on battery life and capacity. He reported battery life reduces if the battery temperature above 30˚C and not recommended to operate EV above 50˚C. But, temperature increases with time continuously beyond 80˚C, which may lead to the initiation of thermal runaway.

Ahmadou Samba [11] reported that battery failure starts with an increase in the temperature above 80 -100 ˚C. So, to avoid failures, it is essential to maintain the temperature of the battery within 80-100 ˚C. Based on this, thermal management of battery pack is essential to keep the battery below 80˚C. Figure 6 shows the battery temperature variation with time under thermal management conditions. The temperature of the battery is below 50˚C.

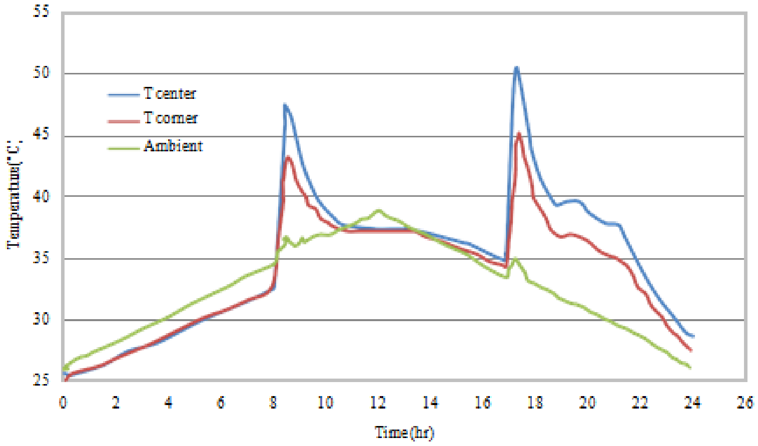


Fig. 7: Battery temperature with thermal management

Thermal management is to maintain the battery at certain temperature to avoid failures when running at higher temperatures. Matt Keyser and Kandler smith [12] reported the battery capacity and life with different cooling techniques. Liquid cooling helps the battery to achieve 10 years duration. J Kim et al. [13] reviewed the battery thermal management cooling techniques and classified the BTM using vapour compression cycle and without vapour compression cycle (Heat pipe, PCM and thermoelectric cooling). They proposed the BTMS using VCC, but these methods consume a lot of energy from AC cooling system. Therefore, the efficiency of battery thermal management reduces. Xia et al. [14] reviewed the battery thermal management methods for cell level and module level. They mainly discussed cell level heat generation, heat transfer and heat dissipation in the cooling system. They have compared the direct cooling method with indirect cooling methods. Shashank Arora [15] reviewed the selection of battery thermal management system for the modular system. He reported that different thermal issues are influencing thermal management performance. Conventional cooling techniques like a fan or cold plate cooling have limited applications. So, he proposed the combination of different cooling techniques for battery thermal management.

However, significant challenges with the battery pack is charging and discharging capacity during cold operating temperature (< 0˚C). Battery capacity drops to 60% due to an increase in the internal resistance of the battery electrolyte at -20˚C temperature [16]. There are many heating techniques to heat the battery when the ambient temperature is < 0˚C. Hence, battery thermal management is to take care of heating the battery during low temp operation. Yan Ji and Chao YangWang [17] proposed the heating strategies for Li-ion batteries under subzero temperature operation conditions. Three strategies were tested for 2.2 Ah 18650 cells from -20˚C to 20˚C. They reported advantages and disadvantages of three heating methods self heating, convection heating and mutual pulse heating. Mutual pulse heating takes less battery capacity to heat as compared to the other two methods.

Battery pack casing is manufactured using aluminium or steel material. Special materials like silicon or carbon non-electric conductive materials are used between battery and cooling system [2]. In all the cooling techniques (air or liquid), non- electric conductive materials are used between the cooling surface and battery surface except few direct liquid cooling methods. These materials are based on silicone properties. Thermal conductivity of these materials is ranging from 1 W/mKto 8 W/mK [18].

Overall, cooling and heating of battery is required to avoid failure of the battery. So, in this work, battery thermal management using different cooling techniques and heating techniques are reviewed and proposed different cooling methodfor battery thermal management. Further, the silicone based materials which are used as thermal interface material in the battery pack are also reviewed in detailed.

1.2 Background & Context

The increasing popularity of electric vehicles (EVs) has brought new challenges to the forefront, one of the most crucial being thermal management. Unlike their internal combustion engine (ICE) counterparts, EVs rely on a complex interplay of high-power electrical components, including batteries, electric motors, and power electronics. These components generate significant heat during operation, and maintaining their optimal temperature range is critical for:

- Performance: Excessive heat can lead to decreased battery capacity, reduced motor power, and compromised efficiency.
- Safety: Overheating can trigger thermal runaway in batteries, posing a fire risk. Additionally, it can damage components, leading to breakdowns and accidents.
- Lifespan: High temperatures accelerate battery degradation and shorten the lifespan of other components.

Therefore, effective thermal management in EVs is essential for ensuring optimal performance, safety, and durability.

Challenges of Thermal Management in EVs:

- Heat sources: Unlike ICE vehicles, where heat is primarily generated in the engine, EVs have multiple distributed heat sources, making temperature control more complex.
- Battery sensitivity: EV batteries are particularly sensitive to temperature variations. Operating outside the optimal range can significantly impact their performance and lifespan.
- Space constraints: EVs have limited space compared to ICE vehicles, making it challenging to accommodate bulky cooling systems.
- Weight considerations: Additional weight from cooling systems can reduce the EV's range and efficiency.

Approaches to Thermal Management in EVs:

- Passive cooling: Utilizing natural convection and conduction to dissipate heat through fins, heat sinks, and optimized component placement.
- Active cooling: Employing pumps, fans, and liquid coolants to actively transfer heat away from hot spots.
- Phase-change materials: Integrating materials that absorb or release heat during phase changes to provide thermal buffering.
- Thermal management system (TMS): Implementing a centralized system that monitors temperatures, controls cooling mechanisms, and optimizes heat transfer throughout the vehicle.

The Future of Thermal Management in EVs:

Research and development efforts are ongoing to improve EV thermal management systems. Some promising areas include:

- Advanced materials: Development of lightweight, high-performance heat transfer materials and phase-change materials with wider operating temperature ranges.
- Integrated cooling systems: Designing compact and efficient cooling systems that are seamlessly integrated into the vehicle's architecture.
- Artificial intelligence (AI)-based control: Utilizing AI algorithms to optimize thermal management in real-time based on operating conditions and battery health.

Effective thermal management will play a crucial role in the continued advancement and widespread adoption of EVs. By addressing the unique challenges of EV heat generation, engineers can pave the way for safer, more efficient, and longer-lasting electric vehicles.

1.3 Scope of the Study

The scope of this study encompasses a comprehensive investigation into the thermal management challenges and solutions within the domain of electric vehicles (EVs). The research focuses on understanding the intricacies of thermal considerations associated with key components of EVs, namely battery systems, electric motors, and power electronics. Additionally, it addresses the broader thermal challenges encountered in the overall vehicle architecture.

1.3.1 Battery Systems

The study delves into the thermal effects on battery performance and explores various thermal management strategies adopted for maintaining optimal battery temperatures. It considers issues such as thermal runaway and the need for temperature uniformity across battery cells.

1.3.2 Electric Motors

A significant portion of the research is dedicated to understanding the heat generation in electric motors and investigating cooling techniques employed to manage motor temperatures effectively. Different aspects of electric motor thermal management, including liquid and air cooling systems, are within the study's scope.

1.3.3 Power Electronics

The thermal challenges associated with power electronics in EVs are thoroughly examined. This includes an exploration of cooling methods and solutions for power electronics components, highlighting the importance of maintaining appropriate temperatures for efficient operation.

1.3.4 Overall Vehicle Thermal Considerations

The study widens its scope to address the broader thermal considerations in electric vehicles. This involves an investigation into the integration challenges of diverse thermal management systems and the impact of overall thermal conditions on the performance and longevity of the vehicle.

1.3.5 Challenges and Emerging Trends

While identifying challenges, the study also explores emerging trends in thermal management technologies for electric vehicles. It considers innovations in materials, simulation models, and optimization techniques that contribute to the ongoing advancements in the field.

1.3.6 Limitations

It is important to note the limitations of the study. The research primarily focuses on thermal management aspects and may not comprehensively cover other aspects of electric vehicle technology. Additionally, specific models or technologies discussed may be subject to rapid developments post the knowledge cutoff date in January 2022.

1.3.7 Geographical and Technological Context

The study's geographical focus is global, acknowledging that thermal management challenges may vary based on climate conditions and regional factors. It also recognizes the evolving nature of electric vehicle technologies, considering the varying thermal management requirements across different generations of EVs.

In summary, this study aims to provide a thorough exploration of thermal management challenges and solutions within the realm of electric vehicles, considering specific components, overall vehicle architecture, challenges, emerging trends, and contextual factors.

II. LITERATURE REVIEW

2.1 Important Definitions of Battery

Following are the basic definitions of battery [19]. The battery is a device consisting of one or more electrochemical cells with external connections provided to electrical power devices such as flashlights, mobile phones and electric cars [20]. Thebattery consists of anode, cathode, separator and electrolyte.

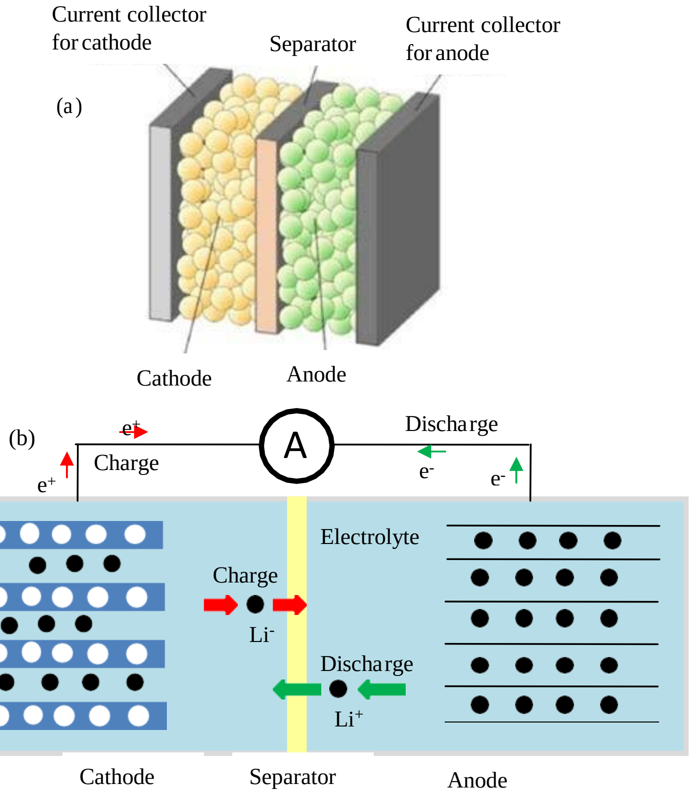


Fig. 8 (a) Structure of the Li-ion cell (b) operation of the Li-ion cell

In a battery cell, the anode is the negative electrode from which electrons flow out towards the external part of the circuit. A cathode is a type of electrode through which electrons move. A separator is a permeable membrane placed between a battery's anode and cathode. They are important to batteries because their structure and properties considerably affect battery performance. Electrolyte serves as a catalyst to make a battery conductive by promoting the movement of ions from the cathode to the anode on charge and in reverse on discharge. The migration of lithium ions in the internal circuit and electrons in the external circuit leads to Li-ion battery operation. Following reactions occurring at LiFEPO4 cathodes (Eq.1) and carbon anodes (Eq .2) during discharging [3].

$$xLi^{+} + Fe^{3+}PO_{4} + (1-x)LiFe^{2+}PO_{4} + xe^{-} \longrightarrow LiFe^{2+}PO_{4} \qquad (1)$$

$$Li^{+}C_{6} \longrightarrow xLi + C_{6} + xe^{-} \qquad (2)$$

2.2Capacity or Nominal Capacity (Ah for a specific C-rate)

The coulometric capacity, the total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100% state-of-charge to the cut-off voltage. Capacity is calculated by multiplying the discharge current (in Amps) by the discharge time (in hours).

2.3 C rate:

A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity.

2.4 Battery Life:

It is the number of the years a device can run on a fully charged battery before the cells fail to operate satisfactorily.

2.5 Heat Generation:

Heat generation is proportional to discharge current (I), resistance (R), temperature(T) and open circuit voltage variation (OCV) with temperature [8].

$$Q_{Gen} = I^2 R + I \times T \times \frac{dOCV}{dT} \tag{3}$$

2.6 Battery Temperature:

Battery temperature increases with an increase in heat generation in the battery.

2.7 Temperature difference (dT):

Battery module temperature difference may lead to temperature hot spot.

2.8 Thermal Runaway:

Initiation of battery layers breaking and explosion due to higher temperatures. Figure 9 shows battery temperature leading to thermal runaway without thermal management.

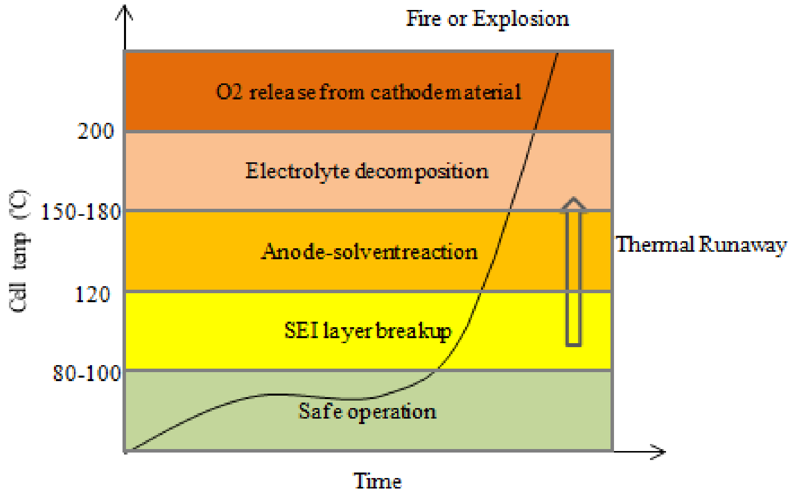


Fig. 9: Battery temperature with time

Out of all the parameters, mainly few parameters are important to asses the battery thermal management like maximum temperature (< 35°C) and temperature difference dT (< 5°C) [20]. These parameters are essential to ensure performance andlife span of the battery [21].

2.9 Overview of Electric Vehicles

Electric vehicles (EVs) represent a transformative shift in the automotive industry, driven by advancements in battery technology and a global push towards sustainable transportation. This section provides a comprehensive overview of electric vehicles, covering key aspects such as:

2.9.1 Historical Evolution

- **Early Developments:** Tracing the roots of electric vehicles from their inception to the present day.
- **Milestones in EV History:** Highlighting significant breakthroughs and technological advancements.

2.9.2 Types of Electric Vehicles

- **Battery Electric Vehicles (BEVs):** Exploring vehicles powered solely by electric batteries.
- **Plug-in Hybrid Electric Vehicles (PHEVs):** Examining hybrid models with both electric and internal combustion engines.
- **Hybrid Electric Vehicles (HEVs):** Understanding vehicles that combine traditional and electric propulsion.

2.9.3 Key Components and Architecture

- **Electric Motors:** Discussing the role and types of electric motors used in EVs.
- **Battery Systems:** Exploring different battery chemistries, capacities, and their impact on vehicle performance.
- **Power Electronics:** Understanding components like inverters and converters crucial for electric propulsion.

2.9.4 Environmental Impact and Sustainability

- **Reduced Emissions:** Analyzing the environmental benefits of EVs in comparison to traditional vehicles.

- **Life Cycle Analysis:** Evaluating the overall environmental impact of electric vehicle production, usage, and disposal.

2.9.5 Market Trends and Adoption

- **Global Trends:** Examining the growth and adoption of electric vehicles on a global scale.
- **Government Incentives:** Discussing policy measures encouraging the adoption of EVs.

2.9.6 Technological Challenges and Innovations

- **Range Anxiety:** Addressing concerns related to the driving range of electric vehicles.
- **Innovations in Charging Infrastructure:** Exploring advancements in charging technology and infrastructure.

2.9.7 Future Prospects

- **Technological Developments:** Predicting future trends in electric vehicle technology.
- **Market Projections:** Assessing the potential scale and impact of electric vehicles in the coming years.

This comprehensive overview sets the stage for a deeper exploration of thermal management within the context of electric vehicles, providing a foundational understanding of the subject matter.

2.10 Importance of Thermal Management

Thermal management plays a pivotal role in ensuring the efficient and safe operation of electric vehicles (EVs). This section examines the significance of thermal management in the context of EVs, covering various aspects:

2.10.1 Battery Performance and Longevity

- **Temperature Sensitivity:** Discussing how battery performance is highly dependent on operating temperatures.
- **Impact on Lifespan:** Analyzing the correlation between thermal conditions and the overall longevity of battery systems.

2.2.2 Safety Considerations

- **Thermal Runaway:** Exploring the potential risks associated with overheating batteries.
- **Fire Prevention:** Discussing the role of thermal management in mitigating fire risks in EVs.

2.10.3 Energy Efficiency

- **Optimal Operating Temperatures:** Examining how maintaining ideal thermal conditions enhances the energy efficiency of electric vehicles.
- **Reduction of Energy Losses:** Discussing how proper thermal management minimizes energy losses during charging and discharging.

2.10.4 Performance Optimization

- **Powertrain Efficiency:** Exploring the impact of thermal management on the efficiency of electric drivetrains.
- **Acceleration and Braking:** Discussing how temperature control influences the performance of electric vehicle components.

2.10.5 Environmental Impact

- **Sustainability:** Analyzing the environmental benefits of efficient thermal management in reducing the overall ecological footprint of electric vehicles.
- **Material Considerations:** Discussing the eco-friendly aspects of thermal management system components.

2.10.6 User Experience

- **Comfort and Convenience:** Examining the role of thermal management in enhancing the comfort of passengers.
- **User-Friendly Systems:** Discussing user interfaces and controls related to thermal management in EVs.

2.10.7 Regulatory Compliance

- **Safety Standards:** Exploring how adherence to thermal management standards ensures compliance with regulatory requirements.

- **Industry Guidelines:** Discussing guidelines set by regulatory bodies for thermal management in electric vehicles.

2.10.8 Technological Advancements

- **Innovations in Thermal Management:** Exploring the latest advancements and innovations in thermal management technologies for electric vehicles.
- **Integration with Vehicle Intelligence:** Discussing the incorporation of artificial intelligence and smart systems in thermal management.

Understanding the critical importance of thermal management sets the foundation for the subsequent exploration of strategies and systems employed in optimizing the thermal conditions of electric vehicles.

2.11 Previous Studies on Thermal Management in Electric Vehicles

Thermal management is crucial for optimizing the performance and lifespan of electric vehicles (EVs). Extensive research has been conducted on various aspects of EV thermal management, with numerous studies exploring different approaches and their respective advantages and limitations. Here's a summary of some key findings from previous studies:

Battery Thermal Management:

- Liquid cooling: This method effectively removes heat from the battery pack using a coolant like water or glycol. Studies by Li et al. (2021) and Zhang et al. (2020) demonstrated significant improvements in battery life and performance with liquid cooling compared to air cooling.
- Phase change materials (PCMs): PCMs absorb and release heat at specific temperatures, aiding in temperature regulation. Wang et al. (2018) reported improved battery cyclability and reduced thermal gradients with PCM integration.
- Machine learning: Utilizing machine learning algorithms for real-time thermal monitoring and optimization has shown promising results. Wang et al. (2022) developed a data-driven control system that improved energy efficiency and reduced thermal stress in batteries.

Motor and Power Electronics Cooling:

- Liquid cooling: Similar to batteries, liquid cooling effectively manages heat in motors and power electronics. Kim et al. (2019) found this method to enhance motor efficiency and extend its lifespan.
- Heat pipes: These passive heat transfer devices efficiently transfer heat away from heat sources to a heat sink. Lee et al. (2017) demonstrated successful heat dissipation using heat pipes in EV power electronics.
- Microchannel cooling: Miniaturized channels within components enable efficient heat removal with minimal coolant flow. Rahman et al. (2020) reported improved thermal performance and reduced weight using microchannel cooling in EV motors.

Overall System Integration:

- Multi-objective optimization: Studies emphasize the need for holistic thermal management systems considering all components (battery, motor, power electronics) and their interactions. Zhang et al. (2021) proposed an optimized system using liquid cooling and PCMs, achieving efficient heat dissipation and improved overall EV performance.
- Lightweight materials: Utilizing lightweight materials for heat sinks and cooling system components can contribute to overall vehicle weight reduction and improved energy efficiency.

Challenges and Future Directions:

- Cost-effectiveness: Implementing advanced thermal management solutions can be expensive. Future research should focus on developing cost-effective and scalable technologies.
- Standardization: Lack of standardized thermal management approaches across different EV manufacturers hinders component interchangeability and wider adoption of advanced technologies.
- Long-term performance: Studies on the long-term performance and degradation of thermal management systems in real-world conditions are crucial for ensuring optimal EV operation throughout their lifespan.

In conclusion, numerous previous studies have provided valuable insights into various thermal management strategies for EVs. Ongoing research continues to refine existing methods and explore novel approaches, aiming to achieve optimal performance, longevity, and cost-effectiveness for EV thermal management systems.

2.12 Current State of Thermal Management Technologies

Thermal management refers to the process of controlling the temperature of a system or object. It is essential in many applications, from electronics and power generation to transportation and building design. Effective thermal management can improve performance, efficiency, and reliability, while also preventing damage from overheating.

There are a variety of thermal management technologies available, each with its own advantages and disadvantages. Some of the most common technologies include:

- Passive cooling: This relies on natural heat transfer processes like convection and radiation to dissipate heat. Examples of passive cooling techniques include heat sinks, fins, and natural air circulation.
- Active cooling: This uses fans, pumps, and heat pipes to actively move heat away from the source. Active cooling is typically more effective than passive cooling, but it is also more complex and energy-intensive.
- Liquid cooling: This uses a liquid coolant to absorb heat from the source and transfer it to a radiator for dissipation. Liquid cooling is often used in high-performance applications, such as computers and data centers, where high heat densities need to be managed.
- Heat pipes: These are sealed tubes containing a working fluid that evaporates at low temperatures and condenses at high temperatures, transferring heat efficiently. Heat pipes are often used in conjunction with other cooling technologies, such as heat sinks and radiators.
- Phase-change materials: These are materials that absorb or release large amounts of heat when they change phase (e.g., solid to liquid). Phase-change materials are used for thermal buffering and heat sinks.
- Thermoelectric cooling: This uses the Peltier effect to convert electricity directly into cooling. Thermoelectric cooling is solid-state and compact, but it can be energy-intensive and is not as effective as other cooling methods.

Thermoelectric cooling thermal management ON Wikipedia en.wikipedia.org

The choice of thermal management technology depends on a number of factors, including the heat load, the desired operating temperature, the available space, and the cost. In recent years, there has been a growing focus on developing new and improved thermal management technologies that are more efficient, sustainable, and cost-effective.

Here are some of the trends in thermal management:

- Miniaturization: As electronic devices become smaller and more powerful, the need for efficient thermal management at the microscale is increasing. This is leading to the development of new materials and heat transfer techniques.
- Sustainability: There is a growing demand for thermal management technologies that are more environmentally friendly. This includes the use of recycled materials, bio-based materials, and low-power cooling methods.
- Integration: Thermal management is increasingly being integrated into the design of devices and systems. This is leading to the development of more compact and efficient systems.

The field of thermal management is constantly evolving, and new technologies are being developed all the time. As the demand for ever-more powerful and efficient devices continues to grow, the importance of effective thermal management will only increase.

III. BATTERY THERMAL MANAGEMENT METHODS

Battery thermal management is essential to maintain the battery operating without any failures. The battery thermal management systems classified in many ways. In the literature, there are many review articles on battery thermal management. J Kim et al. [13] classified the battery thermal management into cooling technique with VCC and without VCC. Rao and Wang [22] first published BTMS review article. They classified the battery thermal management using heat transfer medium air, liquid and phase change material.

In this work, battery thermal management classified using direct contact or indirect contact with battery and heating methods. Figure 10 shows the different methods to cool the battery during hot operation and heat the battery during cold operation.

Battery temperature maintained as per the requirement using

(1) Direct cooling

- Direct Air cooling, Direct Liquid cooling, Silicone based material cooling and PCM cooling method

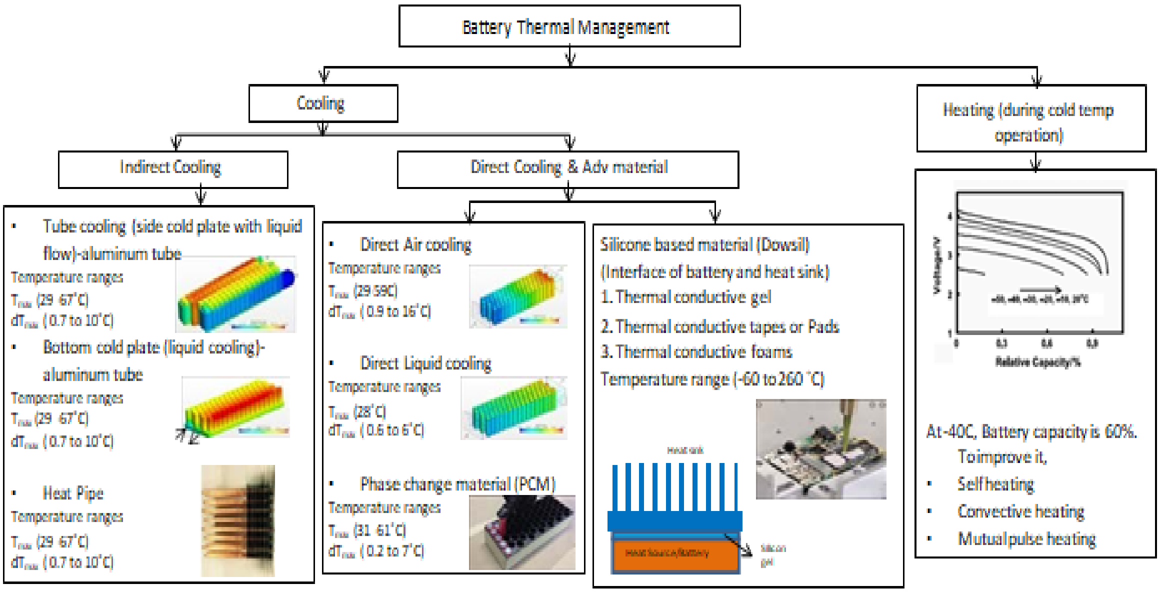


Fig. 10: Battery thermal management methods

(2) Indirect cooling methods

Side tube cooling method, Bottom tube cooling method and Heat pipe cooling method During cold temperature operation, following heating methods are used.

(3) Heating Methods

Self heating method, Convection heating method and Mutual pulse heating method

Silicone based thermal interface material (TIM) have used between the battery and the cooling surface for all the cooling methods. Silicone based materials are in gel type, pads and foams. Heating methods are self heating, convective heating andmutual pulse heating methods.

Most of the EV manufacturers (Tesla & General Motors) uses indirect cooling plus silicone based materials to maintain the battery at the required temperature. Air cooling is an inefficient method as compared to the liquid cooling method. PCM cooling has limitation in maintaining the battery temperature. Heating during cold temp operation is essential to avoid catastrophic failures. Battery capacity is 60% at -20 °C as compared to 100 % capacity at 20°C.

IV. MODELING AND SIMULATION OF THERMAL MANAGEMENT SYSTEMS

4.1 BTM using Indirect Cooling Technique

Indirect cooling of the battery means without fluid flow contact with battery surface. Following are the indirect cooling techniques of BTM.

4.1.1 Side Tube Cooling:

In this method, a separate tube has placed between the battery cells, which consist of a liquid cooling medium (ethylene- glycol). The heat from the battery transferred to tube material, and then the liquid in the tube takes the heat due to convection heat transfer.

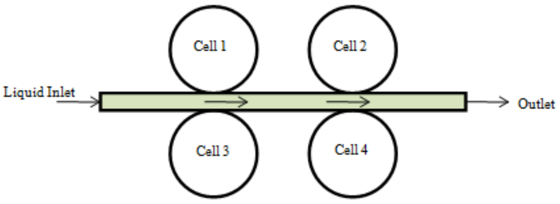


Fig. 11: Side tube cooling

Seyed Mazyar H. M [23] studied the side tube cooling for the cylindrical cell type battery, as shown in the Fig.11. He has used ethylene –glycol as cooling medium and predicted temperature distribution under 2W heat generation. He reported that the temperature difference across the battery pack is around 5˚C. Many automotive companies widely use side tube cooling method. Tesla uses this technique for cylindrical type batteries [24]. General Motors uses a side plate with channels to cool the battery for pouch type batteries [24]. The cooling of heated fluid has done using either the AC system or separate heat exchanger [13].

4.1.2 Bottom tube cooling:

In this method, a tube with fluid flowing from one end to other end kept below the battery pack. The heat from the battery transferred to tube material due to conduction. Then liquid in the tube takes the heat due to convection.

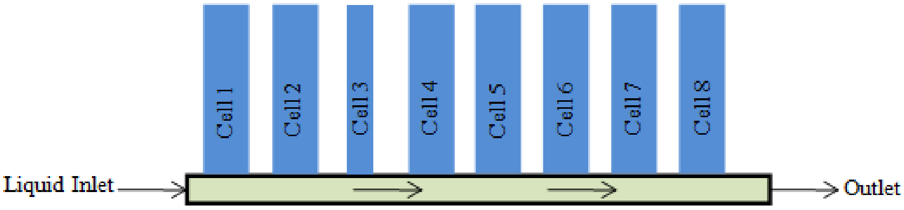


Fig. 12: Bottom tube cooling

Seyed Mazyar H. M [23] studied the bottom tube cooling for the cylindrical cell type battery, as shown in Fig. 12. He has used ethylene –glycol as cooling medium and predicted temperature distribution under 1.24W heat generation. He reported that the temperature difference across the battery pack is around 5˚C. The cooling method shows poor performance when it comes to the internal temperature gradient of the cells. However, the temperature distribution in a module is even. Many automotive companies widely use bottom tube cooling method.

4.1.3 Heat pipe cooling:

The heat pipe is a heat transfer device that combines the principles of both thermal conductivity and phase transition to effectively transfer heat between two solid interfaces [25]. Heat pipe main components, Evaporator side- hot side, Condenser side- cold side (cooling fins), Wick (porous medium), Working fluid and Heat pipe solid material (aluminum or copper). The operating temperature range for a copper/water heat pipe is roughly 25° to 150°C. At lower temperature, fluid properties limit the heat transfer. Water, acetone and butane are the working fluids in heat pipe based on the application. Heat pipes are placed between the batteries, as shown in Fig. 13. One side of the heat pipe is connected to the battery to take the heat. The other side of the heat pipe has kept outside to cool. The working fluid takes the heat from the battery side and vaporizes. The vapour travels to the cold end of the heat pipe and becomes liquid. Liquid travels to hot end through capillary or gravity. Andrey Belyaev et al. [26] studied the flat type heat pipe for Li-ion batteries operating temperature between 20- 47˚C range. They reported that the temperature gradient across the battery is around 3˚C, and maximum heat resistance appears at the radiator rib area.

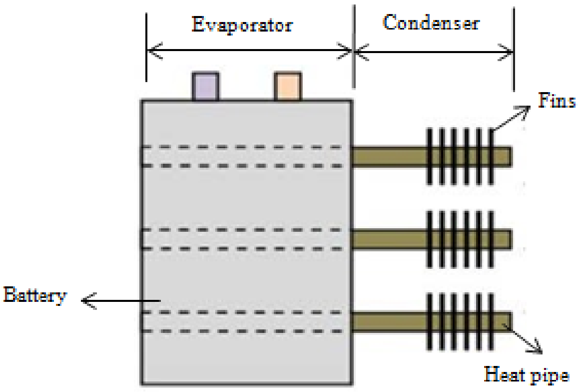


Fig. 13: Battery cooling using heat pipe

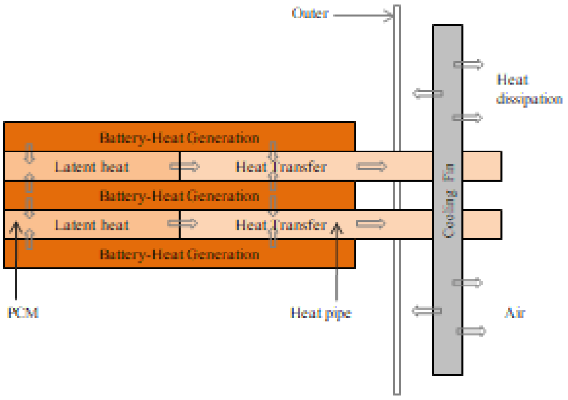


Fig. 14: Heat flow through heat pipe with PCM

Fei-Fei Liu et al. [27] proposed micro heat pipe cooling with forced convection, as shown in Fig. 13. This method can keep the maximum temperature of the pack within 40°C under 3C discharging. This method effectively reduces the instant temperature to increase. It reduces the temperature fluctuation of the pack during transient federal urban driving schedule (FUDS) road conditions. Tatsuya et al. [28] studied the battery thermal management for A4 sized batteries using PCM and heat pipe cooling method. Details of heat flow from the battery to PCM and heat pipe & PCM to heat pipe in Fig. 14. They have achieved battery temperature < 80˚C with combination PCM paraffin and Heat pipe. Advantages and disadvantages ofheat pipe are listed in Table 2.

Table 2: Advantages and disadvantages of heat pipe

Advantages	Disadvantages
Heat exchange throughdirect contact	Costly construction
Construction is simpler andless costly	If condensate contains impuritiescannot be reused
Maintenance is simple	Extra cooling power required
Requires less space	-

Ri-Guang Chi and Seok-Ho Rhi [29] studied the oscillating heat pipe (OHP) for Li-ion battery thermal management. They reported OHP normally operated under 1-5 deg angle. The heat transfer performance of the OHP system has found to be mainly dependent on the filling rate of the working fluid. Working fluids for battery cooling are water, acetone and alcohol in heat pipe based on the application. Bambang Ariantara et al. [30] reported that maximum evaporator temperature with alcohol and acetone is about 50˚C, which is within the operating temperature range of standard lithium-ion batteries.

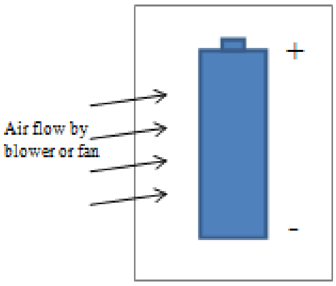
Battery thermal management using heat pipe helps to maintain the battery temperature within the safe operating zone. For better thermal management, heat pipe along with PCM or cooling fins have used to maintain the battery temperature below 50˚C. The heat pipe has used with different working fluids based on the range of battery temperature.

4.2 BTM using Direct Cooling Technique

Direct cooling of the battery means fluid flow contact with the battery directly. Following techniques is the direct cooling ofBTM.

4.2.1 Air cooling

For battery thermal management, air can be used as a cooling medium to cool the batteries. In this method, air forced to flow over the battery pack and carry the heat, as shown in Figure 15 and 16. For example, air cooling technique is used in Toyota prius and Nissan leaf [24]. Air cooling technique can be used as a cooling medium for battery due to its simple construction and low cost. However, low heat carrying capacity and low thermal conductivity may not be suitable for an excellent cooling system. Air cooling is either natural convection or forced convection. For forced convection, the fan required to displace the air [23].



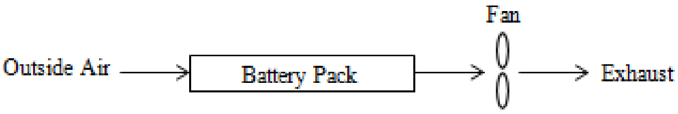


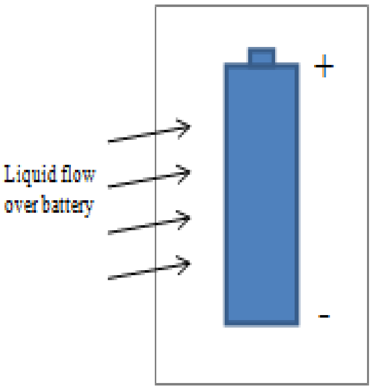
Fig. 15: BTM using direct air cooling **Fig. 16:** BTM using direct air cooling

Air cooling for a set of batteries may cool sufficiently for batteries close to the inlet as compared to batteries at outlet due toits low heat capacity. This may lead to higher temperature differences in the battery pack [23].

The effect of fan position for different cylindrical type battery arrangement has studied by Wang et al. [31]. From the results, they observed that the best cooling effect is registered when the fan is on the top of the battery module. Mahamud etal. [32] performed CFD simulation for cylindrical cells. They reported that using reciprocating airflow can significantly improve the thermal performance of a battery module. Hsiu-Ying Hwang et al. [33] studied the air cooling system for a battery pack of an electric vehicle. It was different from the traditional series ventilation system by changing the locations of cooling air inlets and outlets, shapes of outlet, and combining with an uneven size of the gap among cells. They indicated that the design of semi series ventilation could effectively reduce the maximum temperature and the maximum temperature difference below the required temperature. The maximum temperature of the cell reduced to 4%, and the maximum temperature difference between the surface and core of the cell has reduced by 8%.

4.2.2 Liquid Cooling

Liquid cooling is widely used method to cool the battery pack because of its efficiency as compared to air cooling method. Liquid has higher thermal conductivity and heat carrying capacity as compared to air. In this method, the liquid has forced to flow over the battery pack and carry the heat, as shown in Figure 17. For direct contact cooling, the liquid must have dielectric property.



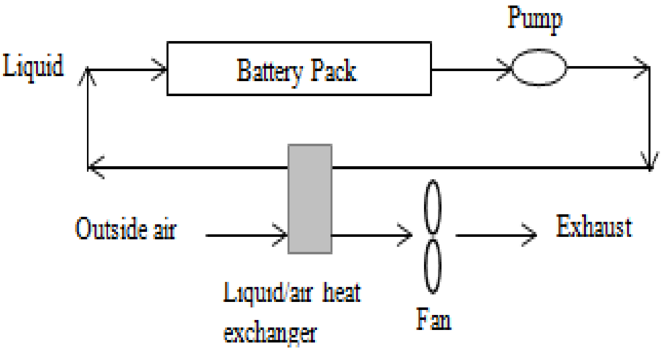


Fig. 17: BTM using direct liquid cooling. **Fig. 18:** Cooling of heated liquid using heat exchangers

The fluid has pumped to flow over batteries in a battery pack to take the heat from the battery cells. The heated liquid is cooled using a liquid air heat exchanger or AC heat exchanger, as shown in Figure 18.

The use of direct contact liquid cooling method had limitation due to special properties like electric non-conductive liquid. 3M developed fluid with dielectric properties [34]. This fluid used for direct contact cooling method for battery thermal management. Seyed Mazyar H. M [23] studied the battery cooling using 3M fluid considering 18650 type cells under heat generation of 4.4 W. He reported that higher temp at the last row of the battery pack, which is due to turbulence created behind the cells. Temperature difference within the cells was < 5°C, which is within the limit of the battery pack. This method is better than direct contact air cooling due to higher heat carrying capacity and thermal conductivity of the liquid.

This fluid eliminates the direct contact material cooling like thermal pads, thermal interface material and potting compounds between cells to maintain the required battery temperature [34].

4.2.3 Silicone based material cooling

Silicone based materials offer superior reliability and long-life performance in many demanding environments as they protect from moisture, dirt, and thermal and physical damage. It is a versatile material that produced in many forms soft gels, encapsulates and foams. For battery thermal management, silicone material is used as gap fillers, encapsulate and the foam [35].

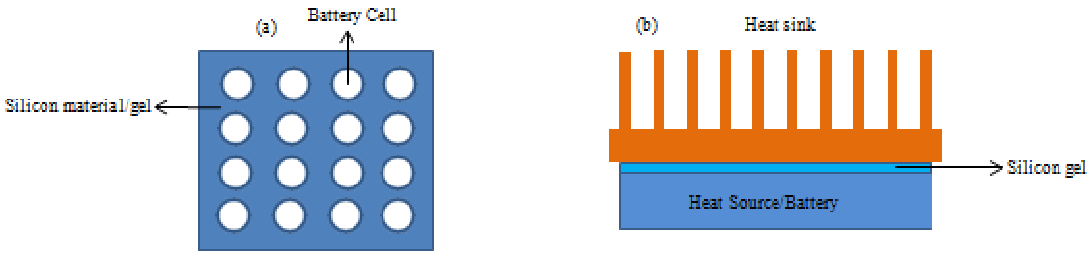


Fig. 19: (a) Battery pack filled with silicon material (b) Silicone material between battery and heat sink

Gap filler material: The gap between the heated battery and the heat sink is filled with the soft gel of silicone material, as shown in Fig 19. This material acts as heat-conducting medium as compared to the air gap between battery and heat sink.

Thermal Interface Material (TIM):

The thermal pad between cell and heat sink is called thermal interface material which is widely used in the battery thermal management [36] due to its thermal conductivity. Silicone based material working temperature ranging from -65°C to 260°C.

Silicone gel helps to fill the air gaps between the hot surface to a cold surface and hence improve heat transfer. It used widely in the electronic cooling application (connecting heat source to the heat sink). This material has properties such as strength, flexibility, thermal management and cell protection.

Silicone gel or sealants may not be used as battery cooling materials completely. It helps to transfer heat from the hot surface to cold. There are many companies manufacturing silicone based materials, which applied to the automotive industry. Dowsil material is widely used silicone material in the electronics cooling application.

4.2.4. Phase Change Material (PCM) Cooling

PCM is a material that accumulates or emits heat by using a process of changing from one state to another at a certain temperature. Phase change materials classified into organic (Paraffin wax) and inorganic compounds [37] as shown in Fig.20. Paraffin wax is widely used PCM material in battery thermal management.

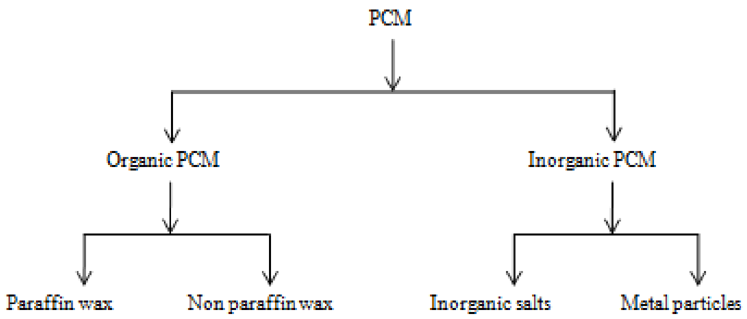


Fig. 20: PCM classification and phase change during heat and cooling

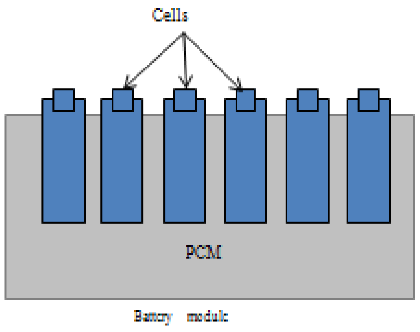


Fig. 21: Battery module with PCM material

Battery thermal management using PCM material widely used in small capacity EV applications [38]. PCM helps to control the battery module temperature as compared to without any cooling. Paraffin wax is mixed with graphite material powder to improve the thermal conductivity of composite material. This cooling technique requires separate cooling to dissipate heat from the PCM material. In Fig 22, aluminium fins are mixed with paraffin wax to cool the PCM material. So, the battery maintained at low temperature as compared to paraffin wax material alone cooling.

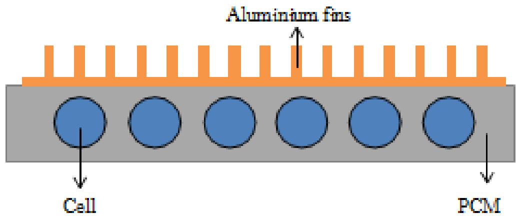


Fig. 22: Battery module with PCM material and Heat sink

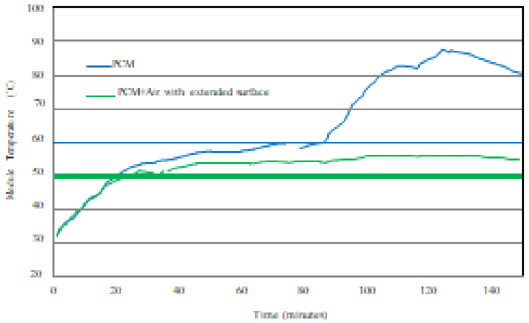


Fig. 23: Module temperature versus Time for PCM cooling [39]

Gi-Heon Kim et al. [39] studied module temperature variation with time, as shown in Fig. 23. They reported battery temperature is very high after 90 minutes if paraffin wax alone used as a cooling medium for the battery pack. It is difficult to operate continuously if the PCM has completely melted due to hot weather or continuous charge/discharge cycles of the battery. Hence, they suggested that additional cooling systems that release the heat of the PCM to the outside. Advantages and disadvantages of phase change material are listed in Table 3.

Table 3: Advantages and disadvantages of PCM material

Advantages	Disadvantages
Reduced peak temperature	Heat accumulation
Temperature control	Undesirable thermal inertia
Reduced system volume	Additional weight
No additional power is required	Need additional cooling system for higher temperature operation

4.3. EV battery thermal management maintenance

The warranty for the battery electric vehicle is about 8 to 10 years. However, some batteries work for nearly 15 years because of usage and maintenance conditions. In most of the battery electric vehicle, the cooling fluid requires special attention to monitor the level of the fluid regularly to avoid battery thermal runaway [40]. So, the regular servicing of the cooling system is essential for battery thermal management.

4.4. New Proposal for Battery Thermal Management

Most of the available battery cooling methods have described in this chapter. However, there is no cooling method using multiphase flow fluid to cool the batteries. In this work, a method has proposed to cool the batteries, as shown in Fig. 24.

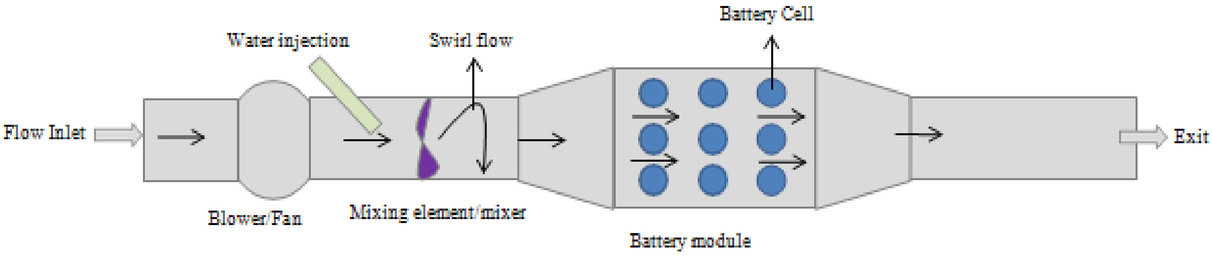


Fig. 24: New proposal to cool batteries using silicone material and air-water mixture

Major components of the proposed cooling system are fan, injector, mixer and silicone materials. Fan or blower is required to pull the air through the battery thermal management system. Water injection system injects water droplets (approximately 10%) into the airflow domain. Mixer between the battery pack and injection system is to mix water and air homogeneously and generate swirl flow before battery pack. Silicone based materials act as a non-electric conductive material between the battery and water-air flow. This method is an improved version of direct air cooling for batteries. In this method, the air is mixed with water droplets before the flow is passing through the battery pack. The mixture of air-water thermal conductivity and heat carrying capacity is higher than air thermal conductivity and heat capacity. So, this cooling medium helps to improve the cooling performance and reduce the high pumping power as compared to air cooling method.

V. EXPERIMENTAL STUDIES AND CASE STUDIES OF HEATING METHODS

Under the condition of cold temperature, the charge-discharge performance of batteries in an electric vehicle is dropped substantially due to the increase of viscosity of the battery's electrolyte and the ascent of internal resistance [17]. So, the available range of EV drops during cold operating temperature below -0°C [40] as shown in Fig.25.

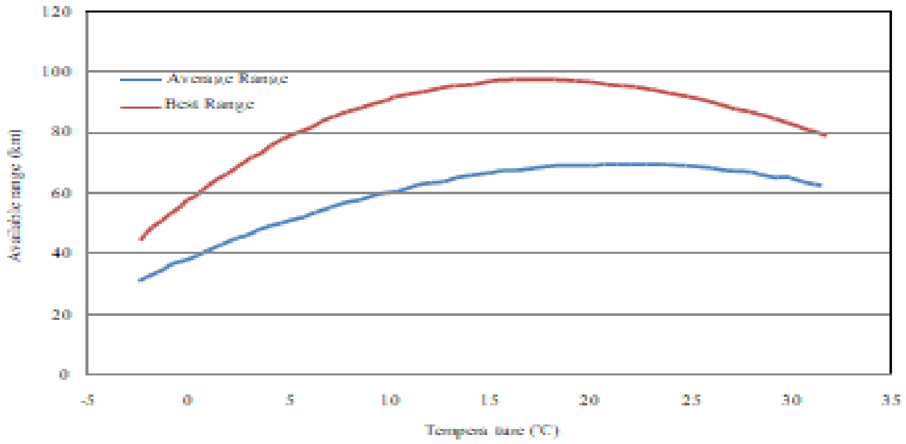


Fig. 25: EV available range versus temperature

Hence, it is essential to have a method to heat the battery system to resolve the cold operation charging and discharge. There are many heating techniques; however, few methods are listed in this section to warm the batteries [16] self-heating, convective heating and mutual pulse heating.

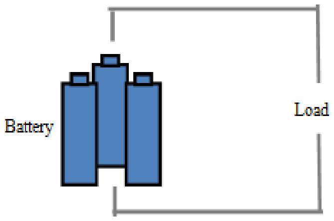


Fig. 26: Battery pack self heating

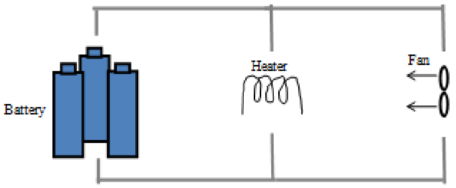


Fig. 27: Battery pack convection heating

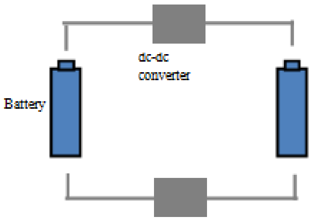


Fig. 28: Battery mutual pulse heating

5.1 Self Heating

In this method, the internal resistance of the cells increases at low temperature, as shown in Fig. 26. Therefore, more heat is generated inside the cells as they start to operate.

5.2 Convective Heating

In this method, the air is blown by the fan over the electric heater, as shown in Fig. 27. The hot air warms up the cells by convective heat transfer. Batteries drive the fan. The convective method is the fastest way of heating.

5.3 Pulse Heating

In this method, the batteries are split into two blocks, as shown in Fig. 28. One block discharged to charge the other block of batteries. This cycle has alternatively repeated between the two blocks. This method is faster than self-internal heating, and it provides more reliable and uniform heating compared to convective heating. This method uses the least battery capacity than the other two.

5.4 Wide-line metal film heating

Zhiguo et al. [42] reported a wide-line metal film heating mechanism to the battery back, as shown in Fig.29. The performance of the battery pack at low temperature is significantly improved. After heating for 15 min at rated power, voltage and power performance of the battery pack was improved at 1C charging and discharging rates. The discharging capacity of the battery pack was restored almost to its room temperature level.

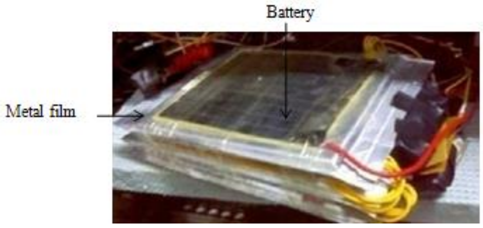


Fig. 29: Battery pack and heater

VI. CONCLUSION

6.1 Summary of Findings

In this work, the existing battery thermal management methods (cooling and heating) were reviewed. In order to ensure optimal battery performance and life span of EV batteries, the selection of battery thermal management system plays an important role.

Indirect Contact Cooling:

Side tube cooling: This method is widely used for 18650 battery cells and pouch type battery cells due to better cooling performance. Tesla uses the side tube cooling method for the battery thermal management of model S. The tube is in the shape of serpentine. The general motor uses the side tube cooling method for the pouch type battery cooling of Bolt model. This method is more efficient to maintain the battery at the required temperature difference (< 5˚C). The side tube helps to hold the batteries firmly during vibration loads.

Bottom tube cooling: This method helps to cool the batteries, but the temperature gradient across the cell is higher than the required temperature (> 5˚C). Hence this method may not be recommended for battery thermal management of the electric vehicle.

Heat pipe cooling: Heat pipe used for cooling the batteries of electric vehicles. For better safe operating temperature, heat pipe along with PCM or cooling fins used to maintain the battery temperature below 50 ˚C. This method is cheaper due to low power requirement as compared to other methods. But it needs extra packaging and additional surface area to cool the condenser side of the heat pipe.

Direct Contact Cooling:

Air cooling: In this method, the maximum temperature difference in the battery pack is high (> 5˚C) due to the last row of cells at the higher temperature. Air has the low thermal capacity, so air takes more heat from the initial row of cells and lessheat from the last row of cells. The high temperature at last row may lead to thermal runaway. Also, this method takes more power to push the air by a fan. It is required to pump more air to improve the performance, which may increase the packaging and cost. Therefore, this method widely used in hybrid cars.

Liquid cooling: In the direct contact liquid method, a special fluid like 3M Novec 774 fluid is used as the coolant since it has a non-conductive liquid. Liquid cooling is the best cooling method as compared to air cooling due to higher heat capacity. Cooling of battery cells is similar to air cooling. So, the last row of batteries cooling is better than air cooling but still required special attention. This method can ensure maximum temperature difference within 5 ˚C. Maintenance of cooling fluid levels in the electric vehicle is mandatory to avoid battery failures.

Phase change material: Battery thermal management uses PCM material to maintain the temperature for small Electric vehicles (scooter). Paraffin wax/Graphite matrix widely used as PCM material in battery thermal management. The major challenge with PCM cooling is maintaining battery temperature at high operating conditions, so it requires additional cooling for high power electric vehicles (passenger cars). Additional cooling systems are forced air cooling and liquid cooling.

Silicone based material:

Silicone based materials utilized as heat conducting medium between battery and heat sink. Hence, the material is called thermal interface material. This material is available in gels, pads, encapsulates and foams. Silicone material working temperature from -65˚C to 260°C. Electric vehicle battery thermal management system uses the silicone based material between the battery and liquid cooling tube. These materials used in most of the thermal management system.

Heating Methods: There are many heating methods to warm the batteries of an electric vehicle. Few heating methods widely discussed in battery thermal management. Self heating, convective heating and mutual pulse heating. Convective heating is better than self heating. Mutual pulse heating is better than the other two methods due to low consumption of battery capacity (5%). All the 3 methods help the battery to heat the battery to 20˚C within 2 minutes.

Expected more demand for electric vehicles in the future. So, the heating load on the EV batteries is higher due to the increased energy density of the battery. Therefore, it would be expected that BTMS consists of combinations of direct/indirect cooling with silicone materials techniques and heating technique. To further reduce the cost and improve the performance of the system, there is still scope to study the multiphase phase flow cooling techniques for battery thermal management.

6.2 Contribution to the Field

In this section, we delineate the distinctive contributions and advancements derived from the present study within the domain of thermal management in electric vehicles (EVs). The research introduces innovative thermal management strategies that go beyond conventional approaches. These novel strategies encompass the integration of advanced technologies, such as artificial intelligence and predictive modeling, aimed at optimizing thermal management systems for heightened efficiency and effectiveness.

Moreover, our study addresses identified challenges prevalent in the realm of EV thermal management. Notably, there is a focused effort on proposing solutions to mitigate the risks associated with thermal runaway in battery systems, a critical concern in ensuring the safety and reliability of electric vehicles. Additionally, we emphasize scalability and adaptability, offering strategies that transcend model-specific limitations and are adaptable to a diverse range of electric vehicle platforms.

A key facet of our contributions lies in the rigorous experimental validation of proposed thermal management strategies. By employing robust experimental methodologies, we aim to provide a solid foundation for the practical application of our findings. The study endeavors to bridge the gap between theoretical advancements and real-world scenarios, thereby establishing the viability of the developed thermal management approaches in actual electric vehicle environments.

Beyond technical considerations, our research delves into the realm of user experience within electric vehicles. We contribute insights into user-centric design principles, exploring how thermal management impacts the overall user experience. Additionally, we investigate human-machine interaction elements, addressing user interfaces and controls that enhance user engagement with thermal management systems, ultimately contributing to a more user-friendly electric vehicle experience.

Furthermore, the implications of our work extend to the industry and policy landscape. We propose industry guidelines for the implementation of thermal management systems in electric vehicles, offering practical recommendations for manufacturers and stakeholders. Additionally, our research provides insights relevant to policymakers, aiding in the formulation of effective policies that support the integration of advanced thermal management technologies in the rapidly evolving electric vehicle sector. Overall, the contributions outlined in this section reflect the multi-faceted impact of our study on advancing the understanding and practical application of thermal management in electric vehicles.

6.3 Recommendations for Future Research

Advanced Thermal Management Strategies:

- Investigate the development and refinement of thermal management strategies, particularly considering emerging battery technologies and evolving electric vehicle architectures.
- Explore the integration of novel materials and alternative cooling methods to enhance the efficiency and sustainability of thermal management systems.

Scalability and Adaptability:

- Address challenges related to the scalability and adaptability of thermal management solutions across diverse electric vehicle models.
- Conduct comparative studies to evaluate the performance of different thermal management strategies under varied environmental conditions and usage scenarios.

Human-Centric Design:

- Refine user interfaces, controls, and feedback mechanisms to ensure a seamless and user-friendly experience with thermal management systems.

- Investigate user preferences and behaviors concerning thermal management settings for the design of intuitive and responsive systems.

Artificial Intelligence Integration:

- Explore the integration of artificial intelligence and machine learning techniques to predict and adapt thermal management strategies in real-time.
- Assess the potential of AI to optimize energy efficiency and ensure the longevity of battery systems.

Industry Collaboration and Standardization:

- Foster collaboration between academia, industry, and regulatory bodies for the successful implementation of thermal management advancements.
- Develop frameworks for standardizing thermal management practices, ensuring safety compliance, and facilitating the integration of these technologies into the broader electric vehicle ecosystem.

These recommendations serve as a roadmap for future research, encouraging exploration and innovation in the dynamic field of thermal management in electric vehicles.

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