Chapter 9
Technical Review on Battery Thermal Management System for Electric Vehicle Application

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Nomenclature

Degree Celsius	Temperature (°C)
volts	Voltage (V)
seconds	Time (s)
Joule/second	Angular momentum (J/s)
1/h	Current 1/h

Abbreviation

EV	Electric Vehicle
PHEV	Plug-in hybrid electric vehicles
BEV	Battery electric vehicle
Li-ion	Lithium-ion
Nicad	Nickel-cadmium
NiMH	Nickel-metal hydride
Li-MnO_2	Lithium manganese dioxide

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Li-(CF)x	Lithium carbon monofluoride
Li-$SOCl_2$	Lithium tetra chloroaluminate
Li-SO_2Cl_2	Lithium tetra chloroaluminate in sulfuryl chloride
Li-$FePO_4$	Lithium iron phosphate
$LiNiMnCoO_2$	Lithium-Nickel-Manganese-Cobalt-Oxide
PEMFC	Proton Exchange Membrane Fuel Cell
PCM	Phase change material
CAE	Computer-aided engineering
TIM	Thermal Interference Material
TR	Thermal runaway
LIB	Lithium-ion battery
BTMS	Battery thermal management system
GRK	Greenhouse gases
TEC	Thermoelectric coolers

9.1 Introduction

The primary challenges to the deployment of large fleets of cars equipped with lithium-ion batteries on public roads are safety, costs associated with cycle and calendar life, and performance. These difficulties are compounded by thermal phenomena in the battery, such as capacity/power fading, thermal runaway, electrical imbalance between several cells in a battery pack, and low-temperature performance. Most batteries should ideally function at an optimal average temperature with a relatively limited differential range. When constructing a battery cell, pack, or system, the rate of heat dissipation must be quick enough to prevent the battery from reaching thermal runaway temperature.

Interest in electric vehicles (EV), which HEVs (hybrid electric vehicles), PHEVs (plug-in hybrid electric cars), and BEVs (battery electric vehicles) are examples of hybrid electric vehicles (BEV), has increased significantly in recent years as environmental regulations regulate greenhouse gases. (GRK) emissions become more severe. Since the turn of the twentieth century, environmental degradation and energy scarcity have become a global problem, with the transportation industry playing an important role. The government has made great efforts to promote electric cars (EVs) for environmental and energy-saving benefits (Johnson et al. 1997), including a number of preferential regulations. The increasing electric vehicle industry requires high specific power and high specific energy density batteries to suit the operational needs of electric cars (Khateeb et al. 2004). Lead-acid, zinc/halogen, metal/air, sodium beta, nickel-metal hydride (NiMH), and lithium-ion batteries are all available for electric cars and HEVs (Li-ion). For FCEV, a proton exchange membrane fuel cell (PEMFC) is also an option. On the one hand, because the battery controls the performance of electric cars, battery safety is an important issue for electric vehicle applications. On the other hand, price is a significant obstacle to the continuity of electric cars for

Table 9.1 Types of cells

Battery type	Nominal voltage V	Specific energy Wh/kg	Energy density Wh/lit	Overview
Lead acid	2.0	30–40	60–75	May et al. 2018)
Nickel–Cadmium	1.2	40–60	15–150	Valøen and Shoesmith 2007)
Nickel-metal Hydride	1.2	30–80	140–300	https://www.powerstream.com, NiMH.htm
Lithium-ion—Classified based on chemistry				
Li-MnO_2 (Lithium manganese dioxide)	3	280	580	Johnson et al. 1997)
Li-(CF)x (Lithium carbon monofluoride)	3	360–500	1000	Greatbatch et al. 1996)
Li-$SOCl_2$ (Lithium tetra chloroaluminate)	3.5	500–700	1200	Morrison and Marincic 1993)
Li-SO_2Cl_2 (Lithium tetra chloroaluminate in sulfuryl chloride)	3.7	330	720	Hall and Koch 1982)
Li-$FePO_4$ (Lithium iron phosphate)	3–3.2	90–160	325	Safoutin et al. 2015)
LiNiMnCoO2 (Lithium-Nickel-Manganese-Cobalt-Oxide)	3.6–3.7	150–220	300	Liu et al. 2020)

both producers and consumers. Therefore, it is very important to optimize battery power and cycle time. In battery-electric cars, lithium-ion batteries are commonly used because of their high specific energy, specific power, energy density (Etacheri et al. 2011; Cosley and Garcia 2004; Huber and Kuhn 2015; George and Bower xxxx; Kim et al. 2019) (Table 9.1).

Because of its better energy density, higher specific power, and lower weight, rechargeable lithium-ion (Li-ion) batteries have been universally acknowledged as the best energy storage solution for electric vehicles (EVs) since the early 2000s. Other rechargeable batteries, such as lead-acid, nickel–cadmium (NiCad), and nickel-metal hydride (NiMH) batteries, have lower rates, lower self-discharge rates, faster recycling, and longer cycle life (Keyser et al. 1999; Bukhari et al. 2015; Li et al. 2014). To improve cycle life, energy storage capacity, and overall performance, it is critical to keep the battery temperature within an acceptable range. This is because lithium-ion batteries are very susceptible to thermal runaway when exposed to high temperatures. This type of lithium-ion battery is very sensitive to temperature, which affects its performance, life, and safety (Scrosati 2011; Zia et al. 2019; Lyu et al. 2019; Liang et al. 2017). In part, this is due to the large variety of electrode materials and electrolyte mixtures used in commercial batteries, making it difficult to establish a consistent and comprehensive process that causes lithium-ion battery performance and safety to deteriorate. On the other hand, it is undeniable that the performance and due to the fact that batteries are influenced by external conditions and emit heat as the result of a series of chemical processes that occur during charging and discharging, temperature changes are almost always unavoidable. As a result, an effective battery thermal management system (BTMS) is needed to maintain the appropriate temperature range of these batteries and to reduce the temperature gradient of these batteries in order to avoid detrimental consequences from temperature fluctuations (Selman et al. 2001; Lin et al. 1995; Saito 2005; Katoch et al. 2020). Elevated temperatures have the potential to ignite very flammable electrolytes, resulting in explosions, fires, capacity loss, and short circuits in lithium batteries. As a result, one of the most essential elements of lithium-ion batteries is the battery thermal management system (BTMS). Battery thermal management may be accomplished via the use of a variety of cooling techniques, including natural or forced air cooling, liquid cooling, and PCM cooling. In electric cars, liquid cooling is often used, while air cooling is more cost-effective in two-wheeler segments, the detailed classification of cooling strategy is given in two types as such (Holzman 2005; Zhao et al. 2015; Liaw et al. 2003)—(a) active cooling strategy and (b) passive cooling strategy. In thermal management systems degradation of cells with increasing temperature can be numerically correlated based on Arrhenius correlation which suggests temperature-dependent physical chemistry profile as the exact relation of electrochemistry with the temperature-dependent design of battery (Qin et al. 2014; Pearce 2015; Lewerenz et al. 2017; Wang et al. 2011; Zhao et al. 2020).

(A) Active cooling strategy—In an active thermal management system to shed out heat from the source an external aid of power is required. Forced convection (Fan cooling), Cold plate cooling, Direct immersion cooling are examples of active thermal management systems. The first active thermal management system was developed in the late 19's which was based on force convection cooling using fans for an electronic application. Over the years with the development of verification and CAE tools active thermal management has become more efficient by using strategic product development such as customized cold plates for avionics application, direct contact dielectric immersion cooling. The active thermal management system has capabilities for a variety of customization to increase conjugate heat transfer characteristics for heat sources (Patil and Hotta 2018; Hotta and Patil 2018; Panchal et al. 2016; Panchal et al. 2016; Panchal et al. 2016; Kurhade et al. 2021; Sun et al. 2019)

(B) Passive cooling strategy—In the passive cooling strategy there is external power required to cool down electronic elements, this system involves utilizing the availability of latent heat from the heat source to cool down the element with ambient temperature. This cooling strategy involves for variety of applications ranging from electronic cooling up to the battery and engine cooling. Extended surface fins cooling, PCM cooling, two two-phasing heat pipes, etc. are some of the examples of the passive thermal management system. Passive systems can be easily customized according to the availability of design space and requirement to pull out the generated amount of heat by making thermal equilibrium. Passive thermal strategy is a very cost-effective approach for economically constrained design since it doesn't require any aid of external power requirement to cool down heat source (Safdari et al. 2020; Chen et al. 2019; Ranjbaran et al. 2020; Ramadass et al. 2002; Liu et al. 2019; Mathew and Hotta 2019; Mathew and Hotta 2020; Mathew and Hotta 2021; Kurhade et al. 2021; Talele et al. 2021).

It should be noted that there are no thorough studies on battery temperature control in the literature. This article discusses the evolution of power battery, including the implications for clean cars and power battery, as well as mathematical models of battery thermal behavior. In the present paper the details of different thermal management techniques are reviewed and contrasted, particularly the PCMs battery thermal management system and the thermal conductivity of materials. This study is anticipated to be beneficial to electric car manufacturers, researchers, and aspirants in the scientific community.

9.2 Battery Thermal Management Systems

9.2.1 Temperature Effect on Battery Performance

The battery cell after 800 cycles at 50 °C, the battery cell loses more than 60% of its original power and 70% at 55 °C after 500 cycles. Lithium-ion batteries have a cycle life of 3323 cycles at 45 °C but drop to 1037 cycles at 60 °C (Hu et al. 2016 Jan 1; Ran et al. 2020; Das et al. 2018). This shows that temperature has a significant effect on battery cycle time and energy capacity. The impact of temperature on the battery life cycle is shown in Fig. 9.1. Automotive batteries are classified into three categories: cells, modules, and packs. Thousands of lithium-ion batteries are connected in various configurations such as series, parallel, or a combination of both to create large-capacity, large-scale battery packs (Wang et al. 2020; Wen et al. 2018; Kim et al. 2012). During the charging and discharging of the battery, a series of chemical processes occur and a large amount of heat is generated, resulting in an unavoidable change in battery temperature (Liang, et al. 2017; Ke et al. 2015; Nagpure et al. 2010). The majority of temperature impacts are caused by chemical processes inside the batteries and also by the materials utilized within the batteries. In the case of chemical processes, the connection between rate and reaction temperature follows the Arrhenius equation, and temperature fluctuation may result in a change in the rate of electrochemical reactions in batteries. Apart from chemical processes, temperature influences the ionic conductivities of electrodes and electrolytes. For example, at low temperatures, the ionic conductivity of lithium salt-based electrolytes diminishes (Jow et al. 2018; Bandhauer et al. 2011; Lisbona and Snee 2011; Finegan 2017). With these impacts in mind, the LIBs used in EVs and HEVs are unlikely to fulfill the United States Advanced Battery Consortium's (USABC) 10-year life expectation. The next sections will address the impacts of low temperature on LIBs as well as the effects of high temperature on LIBs. At elevated temperatures, the consequences are

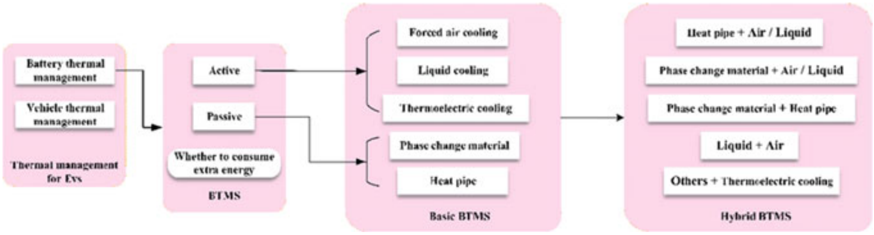
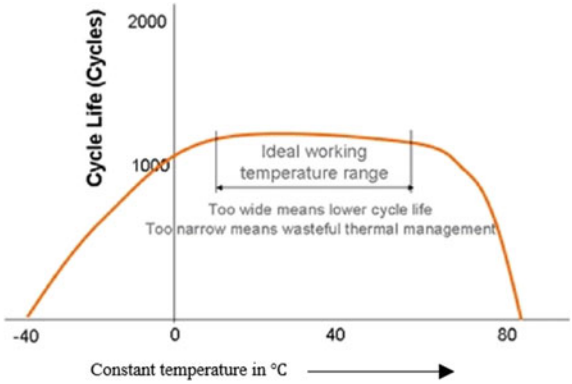


Fig. 9.1 Battery thermal management system classification (Patil and Hotta 2021)

Fig. 9.2 Effect of temperature on battery life



much more complicated than at low temperatures. Heat is produced within the LIBs during operation and knowing how this heat is generated is important for reducing the high temperature impacts in LIBs (Fig. 9.2).

9.2.2 *Thermal Runaway Propagation in Lithium-Ion Batteries*

Thermal runaway in lithium-ion (Li-ion) battery occurs when a cell, or a region inside a cell, reaches dangerously high temperatures as a result of thermal breakdown, mechanical failure, internal/external short-circuiting, or electrochemical abuse, among other causes. Exothermic breakdown of the cell components starts when the temperature is raised over a certain point. At some point, the cell's self-heating rate exceeds the rate at which heat can be dispersed to its surroundings, causing the temperature of the cell to increase exponentially and the cell to lose its capacity to maintain its stability. As a consequence of the loss of stability, all of the remaining thermal and electrochemical energy is released into the surrounding environment. Thermal runaway events may be triggered by a variety of factors. It is possible for a thermal runaway to be triggered by mechanical or thermal problems. Thermal runaway may also be triggered by electro-chemical abuse, such as overcharging or over-discharging battery cells. Additionally, there is the potential of an internal short circuit occurring inside the cell, which may result in thermal runaway (Blomgren 2017; Kim et al. 2007; Liu et al. 2020). The occurrence of any of these events may result in increased temperatures that are high enough to cause the rapid exothermic breakdown of the cell's constituent components. To understand why we observe such fast heating rates, we must first get a better understanding of the breakdown processes that are taking on. A Li-ion cell, or a tiny area inside a Li-ion cell, reaches a specific critical temperature range, at which point the components contained within the cell begin to break down and break down. In nature, these breakdown processes are exothermic, which is why we see self-heating behavior as a result of them. The decomposition rates, which are directly related to the exothermic self-heating rates, also follow the Arrhenius form, which implies that the decomposition rate, therefore, the self-heating rate increases exponentially as the temperature increases. Simply said, when the temperature rises, the rate of decomposition accelerates, and the rate of self-heating accelerates in the same way. The consequence is a rise in the self-feeding heating rate inside the cell, which continues to grow until the cell loses stability and ruptures, releasing all the remaining thermal and electrochemical energy into the surrounding environment (Feng et al. 2018). Although over the past years research importance for thermal runaway was not given so much over the recent application of lithium battery for energy storage increases for heavy-duty applications such as Buses, Heavy trucks, Cranes, etc. which demand a higher amount of power to propel the application which causes certain infield failure in the system as if one of the cells goes in thermal runaways, it causes interaction of the whole module which causes serial breakdown of desired application hence due to safety concern in strategy product design thermal runaway must give importance. In recent years several academic, as well as industrial research initiates, were taken to account the behavior of thermal runaway condition which is summarized in Table 9.2.

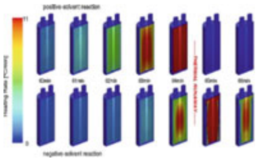
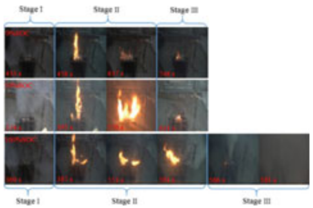
Over the years the problem of thermal runaway causes severe breakdown in working operation of automotive, Table 9.3 shows some examples of recent accidents caused by thermal runaway of automotive.

The abuse condition in Lithium-ion battery can be unpredictable from the Table 9.3, it is reviewed that causing field failure of the a lithium-ion battery can be any which leady cell causing thermal runaway for example vehicle leading to the crash causes mechanical abuse which leads to the thermal runaway, overcharge of battery also causes local thermal runaway of the cell which spreads wide over the pack, internal short circuit also leads to thermal runaway conditions. The categorization of thermal runaway can be classified as below.

9.2.2.1 Mechanical Abuse

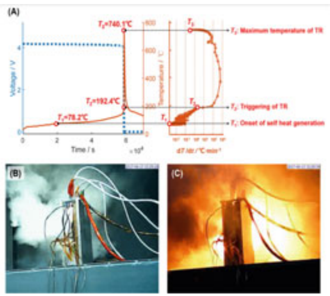
Mechanical abuse is characterized by destructive deformation and displacement produced by an applied force. Mechanical damage often occurs as a result of a vehicle accident, crushing or penetrating the battery pack (Xia et al. 2014b). During a vehicle

Table 9.2 Thermal runaway mitigation

Thermal runaway	Image	Highlights	References
Thermal abuse based on overheating		The model findings indicate that smaller cells reject heat more rapidly than bigger cells, which may save them from thermal runaway under similar abuse circumstances If local hot spots are simulated within a large cylindrical cell, the three-dimensional model predicts that the reactions initially propagate in azimuthal and longitudinal directions and form a hollow cylindrical reaction zone	Wang et al. (2021)
Overheating causes thermal runaway and fire behavior in lithium iron phosphate batteries		A large prismatic Lithium-ion battery are studied A heating plate is placed in the battery which heats them evenly as TIM In thermal runaway propagation cell has shown steady-state combustion rather than instantons No jet fire at 0% Soc The jet fire occurred in 50% to 100% Soc A blow of gas observed after jet fire	Two-way nonlinear mechanical-electrochemical-thermal coupled analysis method to predict thermal runaway of lithium-ion battery cells caused by quasi-static indentation (2020)

(continued)

Table 9.2 (continued)

Thermal runaway	Image	Highlights	References
Internal short circuit causing Thermal Runaway time sequence map for Lithium-ion batteries		The TSM (thermal runaway) mechanism of lithium-ion batteries is proposed in this article. The graphical approach depicts the major physical/chemical processes during battery TR. The TSM depicts the fundamental mechanics of battery TR by sequencing important physical/chemical processes. Two battery samples' TR findings validate the TSM The internal short circuit (ISC) is critical to trigger the oxidation–reduction reaction but is not the major heat source that heats the cell to 800°C or more. The TSM also depicts the battery TR research horizons It recommends future battery TR research should concentrate on: (1) the connection between ISC and TR; (2) the mechanism of the oxidation–reduction process between the cathode and anode; and (3) precise reaction mechanisms for a particular thermodynamic system inside the cell	Bt10m Porsche up in flames as battery charging goes wrong. (2018)

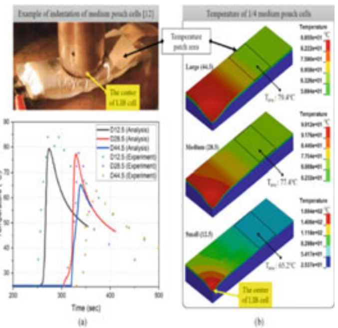
(continued)

Table 9.2 (continued)

Thermal runaway	Image	Highlights	References
Thermal runaway due to over charging		In this study, four 40 Ah Li-ion batteries with varying cathode materials were overcharged The overcharge process has five phases The LFP Li-ion cell experienced TR first, followed by the NCM111 Li-ion cell In NCM Li-ion cells, the duration between TR reduces as the cathode nickel ratio rises For cathode materials, the TR risk is LFP > NCM811 > NCM622 > NCM111, while the overcharge tolerance is LFP > NCM811 > NCM622 > NCM111 NCM811 > NCM622 > NCM111 > LFP Overcharge tolerance (or low TR risk) of NCM Li-ion cells is superior to LFP Li-ion cells (or less TR hazards) The thermal stability of cathode materials decreases with an increasing nickel content in NCM Li-ion cells, increasing TR risks	CGTN (2019)

(continued)

Table 9.2 (continued)

Thermal runaway	Image	Highlights	References
Thermal abuse modeling based on the mechanical indication		An internal short circuit produced by quasi-static indentation may be analyzed using a two-way nonlinear mechanical–electrical-thermal coupled analytical model The material nonlinearity of the LIB components was utilized to determine the mechanical deformation and internal short-circuit induced by cathode–anode contact The thermal model computed temperature using a heat conduction equation based on the electrochemical model's Joule, reversible, and irreversible heat sources A study of mechanical-electrochemical-thermal coupled estimated the internal short-circuit, heat, and temperature increase in each timestep. To test the linked analytical model, 3.2 Ah pouch cells were indented with spherical punches of three sizes An internal short-circuit was predicted by the three indentation tests by 3.3%, and the response force by 5.3% Moreover, the peak temperature owing to thermal runaway reduced with increasing indenter diameter, according to the findings	Sun et al.

(continued)

Table 9.2 (continued)

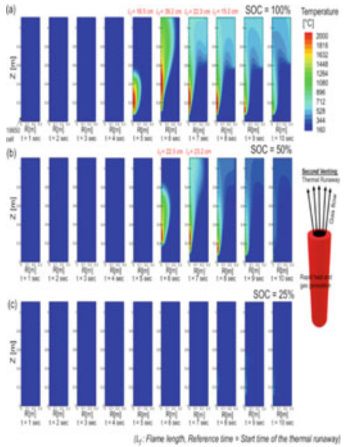
Thermal runaway	Image	Highlights	References
18,650 lithium-ion battery thermal runaway cell venting and gas-phase reactions		We examined the flow and thermal behavior of the existing numerical framework and categorized venting occurrences into two stages: cell breach (internal gas pressure exceeds venting pressure) and thermal runaway We found that the initial stage had little impact on propagation propensity The bulk of reactive gas production happens during the second stage of thermal runaway The quantity and concentration of reactive gas (H_2, CO_2, CH_4, etc.) tend to rise with state-of-charge (SOC) Furthermore, during thermal runaway, the pressure inside the cell casing rises (up to 4.25 bar at 100% SOC) and may trigger a pressure-induced side-wall rupture Also, with larger SOCs, heat from gas-phase reactions may dominate overall heat production, implying that gas-phase reactions cannot be disregarded for safe battery design The numerical framework developed here will be used to compare different cell choices and packaging architectures for next-generation battery modules, taking into account not only thermal runaway propagation due to heat conduction but also thermal runaway propagation due to heat convection and reactive flow	Blanco (2013)

Table 9.3 Thermal runaway propagation through accident

Location	Picture	Accident cause	Reference
Chogging China		Spontaneous ignition causing a fire	Lambert (2017)
Thailand		Fire peak due to overcharge	Zhang et al. (2015)
Seattle, USA		A Model S Tesla caught fire after a road collision. Mechanical abuse thermal runaway	Xia et al. (2014a)
Austria		Tesla Model S crashed into a semi trailer causing a fire. Mechanical abuse post-crash thermal runaway	Maleki and Howard (2009)

accident, it is very likely that the battery pack may be deformed. The arrangement of the battery pack onboard the electric vehicle has an impact on the battery pack's collision reaction. The deformation of the battery pack may have the following potentially hazardous consequences: It is possible that: (1) the battery separator may be ripped, resulting in an internal short circuit (ISC); (2) the flammable electrolyte will spill, with the potential for the battery to catch fire. Studying the crush behavior of a battery pack at several scales, from the material level to the cell level and finally to the pack level, is required. To verify the design under durability conditions several CAE investigations perform on battery packs such as frequency responses, NVH, deformation, etc. (文浩, 谢达明, 罗斌, 梁活开. 动力锂电池安全国家标准 GB, T 31485 与 IEC 62660–3 的比较. 收藏. 2018;11; 杨桃, 邹海曙, 吉盛, 黄伟东 2019; Menale et al. 2021).

Penetration is another frequent occurrence that may occur after a vehicle accident and is difficult to predict. When compared to the crush circumstances, severe ISC may be initiated very instantly after penetration begins to take place. Penetration is controlled in certain mandatory lithium-ion battery test standards, such as GB/T 31,485–2015, SAE J2464-2009, and others, in order to mimic the ISC in the abuse test, for example. Mechanical destruction and electrical shorting take place at the same time, and the abused state of penetration is more severe than the abuse condition of simple mechanical or electric abuse alone. On the nail penetration test of lithium-ion batteries for electric vehicles, difficult issues are being presented. Previously, the nail penetration test method was considered to be a replacement for the ISC's other test approaches. The reproducibility of the nail penetration test, on the other hand, is being called into question by battery makers. Some think that the lithium-ion battery with greater energy density would never pass the nail penetration test in standards, and as a result, a revolution is taking place in the battery industry. The issue of whether to improve the repeatability of the penetration test or to look for a replacement test method remains an open and difficult one in the field of lithium-ion battery safety research (Roth and Doughty 2004; Bugryniec et al. 2018; Leising et al. 2001; An et al. 2019; Zhao et al. 2016).

9.2.2.2 Electrical Abuse

In lithium-ion batteries thermal runaway propagation due to electrical abuse can be classified in 3 main types such as—(a) External short circuit, (b) Internal short circuit (ISC), (c) Overcharge and (d) Over discharge.

(a) External short circuit—an external short circuit can occur if two electrodes with a voltage difference are connected to each other through conductors. Deformation after a vehicle accident, immersion in water, contamination with conductors, or an electrical shock during maintenance are examples of external shorts that can occur with battery packs. The heat generated in the circuit of an external short circuit does not usually heat the cell in the same way compared to penetration. For the most part, external shorting behaves more like a rapid discharge process, with the peak current limited by the material transport rate of the lithium ions. The use of electrical protection devices can minimize the risk of an external short circuit. The main function of protection devices is to disconnect the circuit in the event of a short circuit with high current. When it comes to preventing external short circuits, fuses are the most effective option. However, devices with a positive thermal coefficient (PTC) can also shut down the circuit if the temperature rises excessively. According to the manufacturer, magnetic switches and bimetallic thermostats are other options to avoid the risk of an external short (Lee et al. 2015; Ren et al. 2021; Huang et al. 2021; Zhang et al. 2017).

(b) Internal short circuit—The ISC is the most frequently seen element of TR. There are CSIs associated with almost all abusive conditions. In general, ISC occurs when the cathode and anode come into direct contact with each other due to the failure of the battery separator. When ISC is activated, the electrochemical energy contained in materials is released spontaneously, creating heat. ISC can be classified into three types based on the failure mechanism of the separator. These are: (1) Mechanical abuse, such as deformation and breakage of the spacer caused by penetration or crushing of the nails; (2) electrical abuse, such as dendrites that pierce the separator, whose growth can be induced by overload/over discharge; (3) Thermal abuse, such as the shrinkage and collapse of the separator with massive ISC caused by extremely high temperatures; (4) Thermal abuse, such as the shrinkage and collapse of the separator with massive ISC caused by extremely high temperatures. Massive ISC, which is often produced by mechanical and thermal abuse, will immediately cause TR to occur. As an alternative, moderate ISC produces minimal heat and does not result in TR being triggered. As the degree of the separator fracture increases, so does the amount of time between the ISC and TR required for energy release. As a result, the likelihood of ISC resulting from misuse is very minimal since all cell products must pass the appropriate testing requirements before they can be sold. However, there is still one kind of ISC, known as spontaneous ISC or self-induced ISC, that cannot be adequately controlled by existing test criteria since it occurs spontaneously. It is thought that the spontaneous ISC is caused by contamination or flaws during the production process. The ISC, which is the most frequent characteristic of TR, deserves more investigation. The following research are encouraged: (1) investigation of the processes behind the progressive growth of the spontaneous ISC; (2) development of a more reliable replacement ISC test; and (3) development of an easy-to-use ISC simulation model. Furthermore, the connection between the ISC and the TR has to be explained and defined. Section 9.4 will examine the function of the International Standards Committee (ISC) in the TR process (Zhu et al. 2020; Chen et al. 2020; Ren et al. 2017; Huang et al. 2019; Mendoza-Hernandez et al. 2015).

(c) Overcharge—Overcharge is one of the root causes of the battery pack going under thermal runaway conditions (Finegan et al. 2016). Overcharge can be one of the most disastrous reasons for the failure of cells which is typically form due to the failure of the battery management system to withhold the required amount of energy in the battery pack. Overcharging is characterized by the production of heat and gas, which are two qualities that are frequent. The ohmic heat and side reactions that generate the heat are responsible for heat production. First, the lithium dendrite develops at the surface of the anode because of excessive lithium intercalation on the surface of the anode. The stoichiometric ratio of the cathode and anode may influence the onset of lithium dendrite development. Lithium dendrite growth is a slow process. Second, excessive de-intercalation of lithium results in the collapse of the cathode structure, which results in heat production and the release of oxygen into the atmosphere. Increased oxygen availability expedites electrolyte degradation, which results in the emission of large amounts of gas. Because of the rise in internal pressure, the cell may begin to vent. The interaction between the active elements inside the cell and the surrounding air may result in increased heat production after the cell has been vented. The result of an overcharge experiment is dependent on the test circumstances. The cell burst when exposed to high current, while it merely swelled when exposed to low current (Wang et al. 2020a; Wang et al. 2020b; Lopez et al. 2015; Feng et al. 2018).

(d) Over discharge—Over-discharge is another potential electrical abuse issue to be aware of. It is inevitable, in most cases, for the voltage discrepancy between the cells in a battery pack to exist. Consequently, if the battery management system (BMS) fails to monitor the voltage of a single cell, the cell with the lowest voltage will be over-discharged as a result. The process of over-discharge abuse differs from that of other types of misuse, and the potential danger may be overestimated as a result. During an over-discharge, the cells linked in series with the lowest voltage in the battery pack may cause the cell with the lowest voltage in the battery pack to be forcefully discharged. While under forceful discharge, the pole of the cell reverses, and the voltage of the cell drops to a negative value, causing anomalous heat production at the overloaded cell. The over-discharge of the cell has the potential to cause the cell's capacity to degrade. During the process of over-discharge, the excessive delithiation of the anode results in the breakdown of SEI, which results in the production of gases such as CO or CO_2, which causes the cell to expand. The discharging is less likely to result in cell fires or explosions, and it is thus less dangerous than overcharging. The little amount of current research on over-discharging is mainly concerned with the effects of shallow over-discharge on the number of battery cycles that may be used (Wang et al. 2019; Yuan et al. 2019).

9.2.2.3 Thermal Abuse

Thermal abuse is the direct cause of thermal runaway in the battery pack. The cause of local heating in a battery pack with a cell spreads out over the pack with localized heating of contact cell. In battery pack overheat of localized cell in thermal abuse condition has not only happened by mechanical/electrical abuse but also by loss contacts with connectors, this may typically cause due to manufacturing defects. With the loss of contact when the pack gets in operational work on road condition, it causes localized heating over the cell which spread in module causing thermal runaway condition (Abada et al. 2018). Thermal abuse can also actuate in hot ambient working conditions for the battery as such when the requirement on delivery power for the vehicle is more, battery pack gets heated at the same time if thermal stability over the cooling system is not sufficient it causes coupling of hot ambient temperature with a thermal load of battery pack, hence cell faces the problem of TR for high C-rate requirement (Kong et al. 2021; Zhang et al. 2020; Lai et al. 2020; Tian et al. 2020).

9.2.3 Thermal Runaway Preventive Strategy

The safety issues associated with lithium-ion batteries (LIBs) have been the most significant barriers to their widespread use in portable electronic gadgets, electric cars, and energy storage systems, among other uses. This kind of issue is caused by flammable solvent-containing liquid electrolytes that may be readily oxidized when exposed to high temperatures, resulting in additional heat buildup and, ultimately, thermal runaway (Yang et al. 2020; Wilke et al. 2017). In concern with the issue of thermal runaway, recently there are several research that has been developed to prevent thermal runaway in highly flammable LIBs which is shown in Table 9.4.

From the literature it is seen that thermal runaway is very stagnant process which can initiate in number of different scenarios, recently several research is developed on electrochemistry, mechanical and thermal mode to prevent cell from going into thermal runaway condition (Jindal et al. 2021; Yukse et al.; Yang et al. 2016; Al-Zareer et al. 2017).

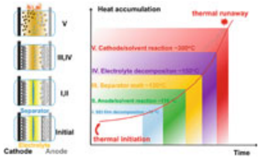
9.3 Active and Passive Cooling Strategy

In BTMS, the primary goal is to maintain stated temperature of cell below 50 °C for efficient working and utilized every cent of available energy from it. In concern with thermal abuse and overheat cell condition, it is essential to design stable thermal management system which increases the thermal stability of cell by preventing it undergoing in overshoot temperature and post-gas dynamic condition in which gas out of the burn cell gets entrap in the enclosure. In the present section, a detailed breakdown of recent research and methodology developed by BTMS is reviewed.

9.3.1 Need of Battery Thermal Management

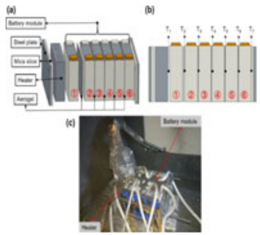
Electrochemical operation and joule heating due to the passage of electrons within a battery cell are the two main sources of heat creation in a battery cell. The temperature

Table 9.4 Thermal runaway preventive strategy

Prevention strategy	Image	Highlight	References
Safe electrolyte for preventing thermal runaway		The design methods for a safe electrolyte may be used to regulate the flammability and volatility of the liquid electrolyte, to avoid thermal runaway, and to finally guarantee the risk-free and fire-free operation of LIBs. A safe electrolyte for LIBs is reviewed here, including the inclusion of flame retardant chemicals, overcharge additives, and stable lithium salts, as well as the use of solid-state electrolytes, ionic liquid electrolytes, and thermosensitive electrolytes. These methods' benefits and disadvantages are contrasted and explored, and a safer electrolyte for future LIBs is suggested	Tian et al. (2020)

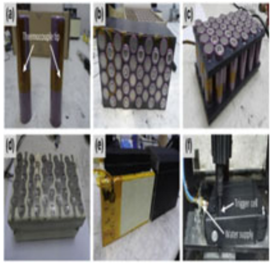
(continued)

Table 9.4 (continued)

Prevention strategy	Image	Highlight	References
Preventing Thermal Runaway Propagation in Lithium-Ion Battery Module Using Aerogel and Liquid cooling plate together		Preventing thermal runaway is important to improving electric car fire safety. The impacts of aerogel, liquid cooling plate, and their combination on the preventive mechanism of thermal runaway propagation are studied. Temperature, voltage, mass loss, and venting parameters during thermal runaway propagation are compared and evaluated. However, adding the liquid cooling plate alone does not seem to stop the thermal runaway propagation, but rather accelerates it. Using aerogel and a liquid cooling plate together may stop the thermal runaway propagation. The research tells us that to successfully avoid thermal runaway propagation, battery thermal management system safety design should include all heat transfer routes	Yang et al. (2020)

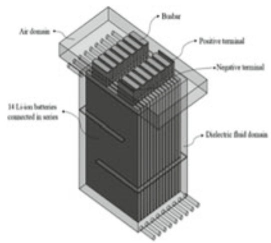
(continued)

Table 9.4 (continued)

Prevention strategy	Image	Highlight	References
Preventing thermal runaway propagation in lithium-ion battery packs using a phase change composite material		Phase change composite materials (PCCTM) provide passive protection at low weight and cost while reducing system complexity. In this study, we compare the efficacy of PCC thermal control in avoiding propagation of thermal runaway in a Li-ion battery pack for small electric cars. A penetration cell causes complete propagation of packs without PCC whereas PCC does not propagate. Packs without PCC may propagate without external short circuits, but not consistently. In all test circumstances, PCC reduces the highest temperature by 60°C or more. On the basis of postmortem data, we deduce the propagation sequence and features of pack failure	Wilke et al. (2017)

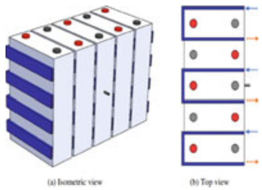
(continued)

Table 9.4 (continued)

Prevention strategy	Image	Highlight	References
dielectric fluid immersion cooling technology to prevent thermal runaway		The MSMD method was used to construct the electrochemical-thermal model of a Li-ion pouch cell with flowing dielectric fluid and tab cooling. The findings of the numerical research and the experimental data agreed within 5%. The maximum temperature of the 50 V battery pack was kept below 40°C for 5°C discharge at 81.7 W. The suggested DFIC aided with tab cooling technique reduced the maximum battery pack temperature by 9.3% compared to the traditional cooling approach. The battery pack reached 341.7 °C when subjected to thermal abuse with an internal short circuit, however the battery pack did not overheat except for the afflicted cell. An effective thermal management technique for high-density and high-capacity Li-ion batteries in electric cars was shown in this research	Patil et al. (2021)

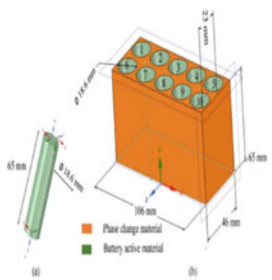
(continued)

Table 9.4 (continued)

Prevention strategy	Image	Highlight	References
Preventing thermal runaway of battery through mini channel cooling		This paper presents a minichannel cooling system for battery modules and tests its effectiveness in preventing thermal runaway. Internal short circuits may be triggered by car accidents or manufacturing flaws. The conjugate heat transport and reaction kinetics models were used to investigate thermal runaway. The impacts of flow rate, thermal abuse responses, nail penetration depth, and nail diameter were studied using numerical models. Minichannel cooling at the cell level cannot stop thermal runaway in a single cell, but it can stop thermal runaway propagation across cells	Xu et al. (2017)

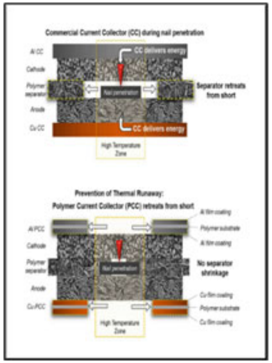
(continued)

Table 9.4 (continued)

Prevention strategy	Image	Highlight	References
Preventing heat propagation and thermal runaway in electric vehicle battery modules using integrated PCM and micro-channel plate cooling system		This technique prevents heat propagation and thermal runaway in a battery module comprised of 18,650 cells damaged by nail penetration of up to three cells. Using the Newman 2D pseudo electrochemical model, short-circuit model, and thermal abuse model, we achieved intense heat production of the order of 106 J/s under thermal abuse conditions. They examined scenarios of 3 cell nail penetration. Heat transmission between three thermally abused cells was avoided by applying 3.9 L min1 water flow and a counter-current flow to two micro-channel plates. The temperature of the cells next to the thermally abused cell was kept below 363 K, avoiding thermal runaway in the battery module. Integrated cooling kept coolant temperature below boiling point at the utilized coolant volumetric flow rate, preventing unwanted circumstances of coolant boiling	Kshetrimayum et al. (2019)

(continued)

Table 9.4 (continued)

Prevention strategy	Image	Highlight	References
Use of polymer—substrate to prevent battery thermal runaway		Protecting electrical components from internal short circuits may help avoid thermal runaway in lithium-ion batteries. A metal-coated polymer current collector is tried in 18,650 batteries to disconnect internal short circuits by drawing from the heating zone. Cells with metal coated polymer current collectors have a decreased danger of thermal runaway during nail penetration. With the use of high-speed synchrotron X-ray radiography and X-ray computed tomography, we can learn more about how 18,650 cells work. It compares to 18,650 batteries with commercial aluminum and copper current collectors. During nail penetration, cells with aluminum-coated polymer current collectors maintained a cell voltage > 4.00 V, whereas conventional cells suffered thermal runaway	Pham et al. (2021)

range of 25–40 °C is excellent for Li-ion batteries, whereas temperatures beyond 50 °C are hazardous to the batteries' lifespan. The immaturity of even a single cell is a deterrent, can significantly affect the overall performance and efficiency of the battery pack, the major goal of the BTMS is to regulate the temperature of the battery's cells and hence extend the battery's lifespan. Active systems and passive systems are the two primary forms of BTMS. The active system is mostly reliant on the forced circulation of a specific coolant, such as air or water. A passive system is one that does not require any action on the part of the user. A passive system, which uses methods such as heat pipes, hydrogels, and phase change materials to have zero power consumption, enhances the vehicle's net efficiency. In this publication, a full evaluation of BTMS is presented based on accessible literature, with research for future advancement highlighted.

9.3.2 Active Cooling Strategy

Active cooling refers to a cooling technology that relies on external equipment to improve heat transfer. Active cooling strategy increases the fluid flow rate in the convection process, thereby significantly increasing the heat dissipation rate. The active cooling solution includes forced air supply by fans or blowers, forced liquid, and thermoelectric coolers (TEC), which can be used to optimize thermal management at all levels when natural convection is not enough to dissipate heat use of a fan is recommended (Table 9.5).

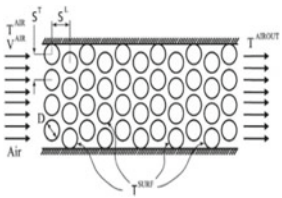
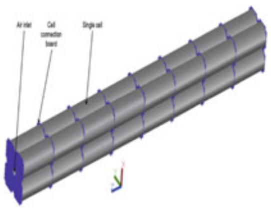
9.3.3 Passive Cooling Strategy

Passive cooling maximizes radiation and convection heat transfer modes by using a radiator or heat sink, thereby achieving a high level of natural convection and heat dissipation. By keeping the electronic products below the maximum allowable operating temperature, can provide adequate cooling and thermal comfort for the electronic products in the home or office building. This growth trend can be observed in Battery Technology commonly referred to as passive Cooling in the industry (Table 9.6).

9.3.4 Hybrid Thermal Management Approach

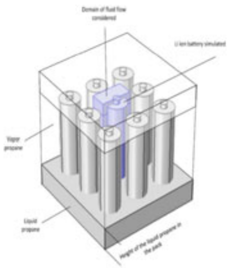
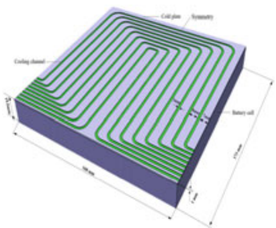
Over the recent years as the demand for energy storage to fulfill power requirement is increased for which the present form of thermal management system cannot fulfill the exact cooling requirement hence hybrid thermal management system approach is widely adaptable for the desired application. In the hybrid approach basic two or more

Table 9.5 Active cooling strategy for BTMS

Research paper title	Image	Highlight	References
Battery thermal management for PHEV over the variety of ambient condition for LFP cell		In this paper, they modeled electric vehicle with an air-cooled battery pack made of cylindrical Lithium iron phosphate cells and simulated the effects of thermal management, driving conditions, regional climate, and vehicle system design on battery life. Developed a simulation model of battery and automatic operation, heat generation, heat transfer, battery degradation during vehicle operation, charging, and idle to estimate the degradation of the PHEV battery under various conditions	Shen et al. (2020)
Investigation of thermal performance of battery pack using air cooling		The thermal performance of axial air cooling for lithium-ion battery packs was investigated with 32 individual cells and solved numerically by coupling the liquid transport equations. To calculate the heat generation rate of the battery pseudo-2D model is used. Numerical simulations are used to study the thermal performance of the air cooling system	Xia et al. (2019)

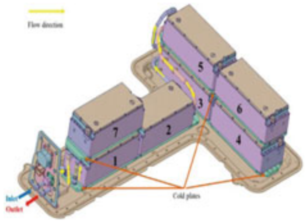
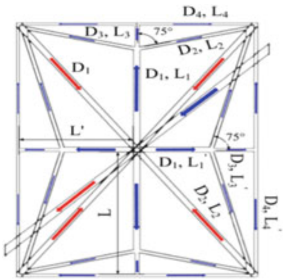
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
A novel study to enhance the thermal performance of the battery pack		This article proposes a new BTMS (Battery Thermal Management System), a PCM for battery packs in hybrid electric vehicles, and a 3D electrochemical thermal model. Liquid propane is used to dissipate a numerical thermo-electrochemical model that studies the performance of the cooling system	Deng et al. (2019)
Thermal Management of prismatic Lithium-Ion cells using liquid cooling		The intention of this investigates a powerful cooling technique of prismatic Li-ion batteries for an electric-powered vehicle, a layout of BTMS, the usage of minichannel bloodless plates is established. The overall performance of the BTMS is parametrically studied with the aid of using the usage of exceptional configurations, glide rates, and inlet coolant temperatures. To remedy the thermal control trouble of a fifty-five Ah Li-ion battery, a minichannel bloodless plate–primarily based totally liquid cooling designed with the aid of using the usage of numerical simulation technique	Wiriyasart et al. (2020)

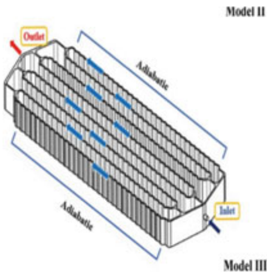
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
Use of liquid cooling for improving the thermal performance of cells in electric vehicle		In this study, a liquid-cooled layout is proposed from the percent stage to enhance the thermal overall performance of cells % primarily based totally on the warmth dissipation strategy, standard thermal control subject turned into deliberate as a reference fashion for the battery %. The 3-d temporary thermal version turned into used	Kalnaus et al. (2018)
Splitting mini-channels cooling plate for prisimatic Li-ion battery design optimization		The work carried out in this article is to optimize the dissipation of cold plates embedded with leaf-shaped mesh according to the structural theory. A distributed network layer has been created, but together with a collection network layer, it has been designed to reduce the inherent disadvantages of standard single-channel gradients. In this article, a leaf-shaped network structure applied as a cold plate for a lithium-ion battery is analytically optimized	Park (2013)

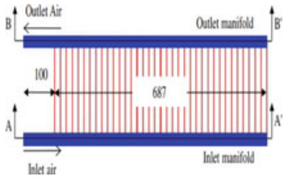
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
Nanofluid cooling of battery packs		The temperature distribution and pressure drop employing nanofluids flowing within the corrugated mini-channel of the EV coil cooling module are described in this paper using a computational analytical approach. There are 444 cylindrical lithium-ion cells in the EV battery module (18,650 type). The refrigerant flow direction, mass flow rate, and refrigerant type were determined to have the greatest impact on the temperature distribution. The suggested module's (model II) most effective cooling performance was achieved with nanofluid as the refrigerant, resulting in a 28.65% lower temperature than the standard cooling module (model I)	Effat et al. (2016)

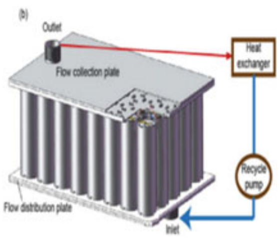
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
Use of cooling plates in electric vehicles		In this study, the effects of inactive components, such as cooling plates and protective shells of modules, on the deformation and failure of individual cells are taken into account. They carried out experiments in the hole of the EV battery module with and without these components. 3 different scenarios were recorded during this study: (i) stacks of cells (ii) stacks of cells with cooling plates inserted in each second cell (iii) stacks of cells with cold plates and with the plastic plate	Choi and Kang (2014)
A design for cooling li-ion batteries in hev using an airflow configuration		In this article, a selected type of cooling coil system is examined on paper to meet the desired thermal specifications battery. In a hybrid electric vehicle, the battery is made up of cells connected in series and parallel configuration, so cooling performance based on the distribution of fluid channels is indisputable that even if the current battery system layout/design is not dynamic, the desired cooling performance can be achieved using the conical elbow and pressure relief vent	Saw et al. (2016)

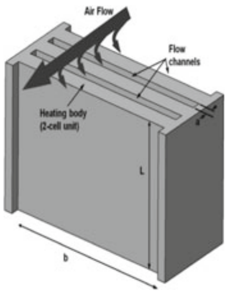
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
A review of modeling efforts in the major areas of heat control and lithium-ion battery cell safety		The objective of this study is to provide an informative summary of the thermal management and safety of LIBs in a very fast but inexpensive way. In this regard, the article discusses the modeling efforts carried out in four main topic areas, namely (1) chemical science models, (2) coupled electrochemical-thermal models, (3) Lithium-ion battery cooling (4) LIB abuse and thermal escape We have a tendency to specialize in modeling due to development and technology style of lithium batteries	Giuliano et al. (2012)

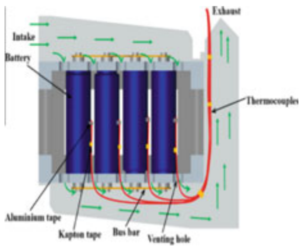
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
Air cooling of the battery pack to examine the thermodynamic behavior		In this research work, an acceptable thermal management system is designed, modeling methodology is proposed that describes the thermal behavior of an air-cooled lithium-ion battery system from the point of view of a vehicle component designer A proposed mathematical model is constructed to support the electrical and mechanical properties of the battery. Validation test results for lithium-ion battery systems are presented The results show that current model can provide a good estimate for simulating convection heat transfer cooling	Jiaqiang et al. (2018)

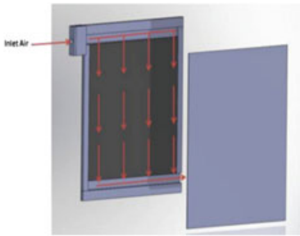
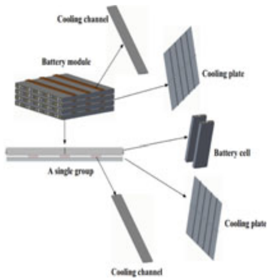
(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
Li-ion battery pack with air cooling: CFD and thermal analysis		The study deals with CFD to analyze the air conditioning system for a 38,120-cell. The pack contains 24 38,120 cells, copper bus bars, intake and exhaust plenums, and support plates with ventilation holes. Accelerated rate calorimeter is used to calculate the heat generation rate during the charging state. The thermal performance of the battery pack was analyzed with various cooling air mass flow rates using steady-state simulation. The simulation results show an increase in cooling airflow which will effect in a rise in the heat transfer coefficient and a decrease in pressure	Sun and Dixon (2014)

(continued)

Table 9.5 (continued)

Research paper title	Image	Highlight	References
Experimental investigation of an air-cooled system for lithium-ion cells		As part of this study, the implementation of an air-cooled system was examined. The authors describe the procedure for the design and testing of an air-cooled thermal management system under laboratory conditions and draw conclusions about its effectiveness. The experimental results provided an idea of the influence of the SOC of the cell on the internal resistance and, therefore, on the general thermal behavior. Designed and manufactured an air that uses metal foam-based insole panels for heat dissipation capacity. Experiments were performed on Altair nano 50 Ah battery on a variety of charge–discharge cycle streams at two airflow speeds	Saad and Oudah January (2022)
An Orthogonal experimental design of cooling battery packs		In order to examine the influence of parameters on the cooling effect of the liquid-based cooling strategy model, an orthogonal array L16 (44) was chosen to model sixteen models to perform and measure parametric to identify primary and secondary factors, then a combined model was found. The results show that the pipe number has the effect on the temperature of the cold plate in four constraints, and the coolant flow rate is the second, the pipe height has the least effect	Buonomo et al. (2018)

(continued)

Table 9.5 (continued)

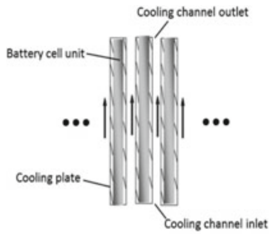
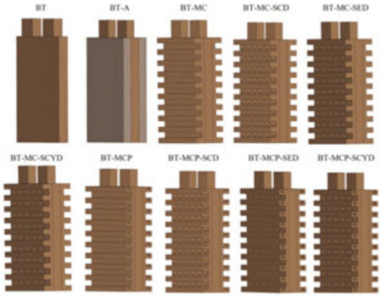
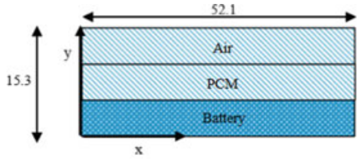
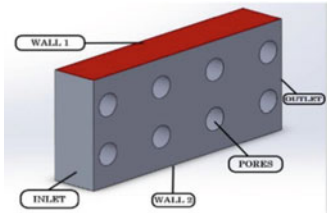
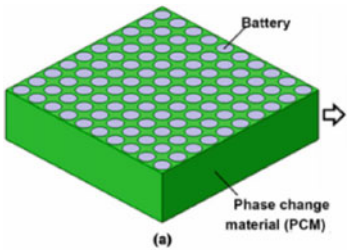
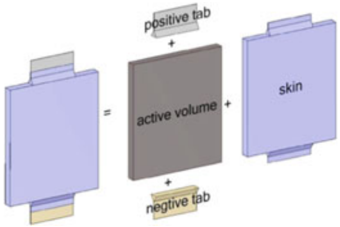
Research paper title	Image	Highlight	References
Use of air cooling method for battery application	 Fig. 2. Schematic of battery cell and its cooling channel.	This article shares a study of the cooling strategy development methodology for cold lithium-ion bag cells used in hybrid electric vehicles (HEV). The 3D transient thermal model of the battery pack was developed by incorporating the three-dimensional flow sub-model of the battery pack, the one-dimensional network sub-model of the battery pack, and the thermal cell/battery module sub-model across the battery cell heat generator attributable to charge transfer rates at the interface of the battery cell solution. and the potential gradient expressed between the types of User Delineated Functions (UDFs)	Harish et al. (2021)

Table 9.6 Passive cooling strategy for BTMS

Research paper title	Image	Highlight	Reference
Using fins and perforations for increasing performance of the battery		In this research work, the fins consists of circular perforations which are used to reduce the battery temperature, fins with circular perforations can be used to reduce the temperature significantly	Song (2018)
Metal foam containing phase transition materials has been used to cool lithium-ion batteries	 Fig.1 Physical Domain	The research work was based on a 2-D domain, in which PCM was used for the delay in critical temperature of the battery pack. The metal foam was used for uniform heat distribution	Chen et al. (2016)

(continued)

Table 9.6 (continued)

Research paper title	Image	Highlight	Reference
Study of thermal behavior of Aluminum foams in batteries of electric vehicles		In this research paper numerical simulation of battery, the model was done with metal foam for high thermal performance. The study determined a 45% reduction in temperature	Fathabadi (2014 Jun)
Influence of phase change material for enhancing thermal performance of lithium ion battery		In this paper, phase change material was filled in the gaps between cells. The study showed that by increasing the spacing between the cells the delay effect can be increased	Javani et al. (2014)
Cooling using phase change material		Researched methods for using phase change materials for cooling and found that they can provide several benefits in limiting peak temperatures. Some researchers have used porous foam or carbon fiber	Bamdezh and Molaeimanesh (2020)

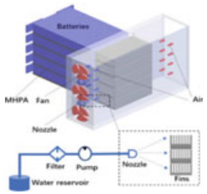
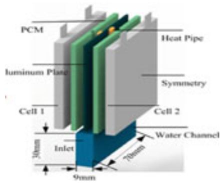
BTMS is combined to generate the maximum amount of heat transfer coefficient to wipe out the desired temperature from the source. To overcome the obstacles and maximize the effectiveness of BTMS, several researchers have suggested a combination of BTMS. This kind of BTMS combines active and passive BTMS, or two passive BTMS, which is referred to as hybrid BTMS. PCMs with air circulation, PCMs with liquid circulation, and PCMs with heat pipes are all often utilized in the modern-day. The below table shows recent research developed in combination strategy for hybrid BTMS (An et al. 2017; Zhao et al. 2020; Bamdezh et al. 2020; Patel and Rathod 2020; Al-Zareer et al. 2017; Hekmat and Molaeimanesh 2020; Jin et al. 2021; Yue et al. 2021; Zhang et al. 2021; Qin et al. 2019) (Table 9.7).

9.4 Conclusion and Future Recommendation

Power cells having big capacity, high energy density, and quick charging are becoming more popular in electric cars, resulting in a broad range of temperature distribution. As a result of the rise in the rate of heat production, batteries have safety issues such as life span ageing, degradation acceleration, and loss of stability. This article examines the thermal model of a battery pack and categorizes the battery thermal management system for battery pack cooling. The need and scope of having a battery thermal management system is also covered in a manuscript. The general classification of BTMS is divided in three segments as shown in Fig. 9.1 Hierarchy. The selection of battery thermal management system is totally dependable on various customization and end-user need, from regressive literature it is found that selection criteria for BTMS depend on associated factors such as cost (if its lower budget application generally passive BTMS is proven as best selection), feasibility to increase HTC, robustness as preventing it undergoing thermal runaway condition which covers in safety functional aspect. Furthermore, regressive literature is developed on the cause of thermal runaway and preventive strategies which can save battery packs from going in a thermal runaway condition. Recent development in BTMS in terms of a hybrid approach to come up with the limitation of the passive thermal management system is also reviewed.

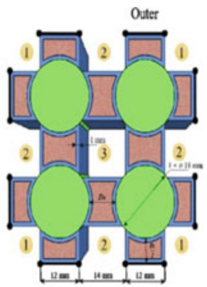
Concluding remark future recommendations are suggested in terms of techno-commercial aspect as of the BTMS which primarily takes into account the relationship between beneficial work production by BTMS and its electric consumptions, may improve the overall economic efficiency of the system predicting the driving environment using the vehicle to everything (V2X) technology that can accurately forecast the output power of the LIB, which has a major impact on temperature increase. To manage the multi-physical BTMS, which includes the preheating system and cooling system, an intelligent control strategy that is self-adaptive and takes economic considerations into account should be developed. Several emerging cooling techniques, such as thermoelectric cooling, hydrogel-based cooling, thermo-acoustic cooling, and magnetic cooling, are emerging today and have the potential to provide many advantages over air cooling or liquid cooling methods, including

Table 9.7 Hybrid cooling strategy for BTMS

Research paper title	Image	Highlight	Reference
Under dynamic working conditions, a hybrid battery thermal management system for electric vehicles		In this study, hybrid cooling is suggested for electric vehicles. The performance using the cooling strategy was increased to 62% which reduced the energy consumption	Behi et al. (2020)
Hybrid technique for Battery Thermal Management System based on PCM, HP, and LP created for surrogate model		The authors suggest a hybrid thermal management system consisting of PCM, HP, and liquid cooling. Based on the Adaptive-Kriging-HDMR technique, a surrogate model is created. Global sensitivity analysis is used to identify four sensitive variables. The improved system is tested under cycling and thermal runaway conditions	Mathew and Hotta (2018)

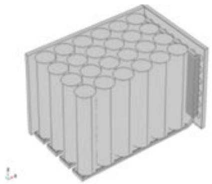
(continued)

Table 9.7 (continued)

Research paper title	Image	Highlight	Reference
Use of PCM and air cooling for novel hybrid technique		This article proposes a new hybrid BTMS that blends air-forced convection and PCM. The proposed BTMS's efficacy was then shown using dynamic cycling at 1 C, 2 C, 3 C, and 4 Crates. Both the maximum temperature and the maximum temperature differential are kept within the specified limits. Meanwhile, thermal performance was evaluated between active and passive cooling. TMax and TMax have both been substantially lowered since the advent of active cooling. Experiments demonstrate that the passive approach is incapable of maintaining the maximum temperature within the optimal range at a pace of 3 C. Additionally, the experimental findings verify the numerical model, which consists of a three-dimensional heat transport model linked with an electrochemical model. The spacing between batteries is further adjusted based on the simulation, and the suggested gap for application is 5 mm	Mathew and Hotta (2021)

(continued)

Table 9.7 (continued)

Research paper title	Image	Highlight	Reference
For electric vehicles cooling battery using air conditioning and heat, pipe		This article proposes a hybrid thermal management system & # 40; TMS' for electric cars using air cooling and heat piping (EV). The thermal behavior of a battery module with 24 cylindrical cells is mathematically and thermally predictable. The difference between natural and forced air cooling TMS is explored. Optimizations include changing cell spacing, air velocity, ambient temperature, and inserting copper foil heat pipes (HPCS). COMSOL Multiphysics® programmed in commercial CFD solves mathematical models. According to the modeling and experimental results, the suggested cooling technique holds for optimizing TMS with HPCS, providing recommendations for future optimization of similar system designs. The maximum temperature of the modules for forced-air cooling, heat pipes, and HPCS are 42.4 °C, 37.5 °C, and 37.1 °C, i.e., 34.5, 42.1, and 42.7% lower than natural air cooling. The battery module temperature uniformity increased by 39.2, 66.52, and 73.42%	Mathew and Hotta (2019)

significant energy and potential savings cost, as well as high potential for scalability and scalability. Then, sensors are used to monitor the operating status of the battery pack, such as its temperature, current, and voltage, which can be used to interact with the temperature prediction model to correct errors in the model. Furthermore, we recommend using data predictive modeling based on multi objective analysis in which the upper bound limit must need to set as per the desired output constraint from end customer to turn a research concept in an actual feasible product that can be easily implemented from a paper to application.

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