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Review

Review on Battery Packing Design Strategies for Superior Thermal Management in Electric Vehicles

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Abstract: In the last decades of electric vehicle (EV) development, battery thermal management has become one of the remaining issues that must be appropriately handled to ensure robust EV design. Starting from researching safer and more durable battery cells that can resist thermal exposure, battery packing design has also become important to avoid thermal events causing an explosion or at least to prevent fatal loss if the explosion occurs. An optimal battery packing design can maintain the battery cell temperature at the most favorable range, i.e., 25–40 °C, with a temperature difference in each battery cell of 5 °C at the maximum, which is considered the best working temperature. The design must also consider environmental temperature and humidity effects. Many design strategies have been reported, including novel battery pack constructions, a better selection of coolant materials, and a robust battery management system. However, those endeavors are faced with the main challenges in terms of design constraints that must be fulfilled, such as material and manufacturing costs, limited available battery space and weight, and low energy consumption requirements. This work reviewed and analyzed the recent progress and current state-of-the-art in designing battery packs for superior thermal management. The narration focused on significant findings that have solved the battery thermal management design problem as well as the remaining issues and opportunities to obtain more reliable and enduring batteries for EVs. Furthermore, some recommendations for future research topics supporting the advancement of battery thermal management design were also discussed.

Keywords: battery pack; design strategies; thermal management; lithium-ion battery; electric vehicles

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1. Introduction

Lithium-ion batteries (LIBs), as energy storage devices, are considered to have a significant role in determining the performance of electric vehicles (EVs). LIBs depend vastly on temperature for facilitating an optimum performance and lifetime, with the commonly suggested operating temperature being in the range from 25 to 40 °C [1,2]. Operation at lower or higher temperatures than the range can adversely affect or degrade the performance and lifetime of LIBs. Lower-temperature operation with a high current rate leads to lithium plating on the anode, capacity loss, impedance rises, ionic conductivity decreases, and internal short circuits due to metallic lithium dendrites [3,4]. Meanwhile, higher-temperature operation could reduce the active materials and increase the internal resistance, even for overly high temperatures, potentially causing thermal runaways that might prompt fires and explosions [5].

LIBs are packaged in relatively small sizes, called battery cells, to allow effective manufacturing; therefore, LIBs need to be electrically arranged in series and parallel connections (called battery modules) to provide sufficient voltage and capacity in powering

EVs [6]. During EV operation, batteries can experience varying temperatures that lead to unbalanced performances. Each cell generates heat from internal resistance (Joule heating) and redox chemical reactions [7]. In the discharging process, the battery experiences an exothermic chemical reaction, while during the charging process the battery experiences an endothermic chemical reaction [8]. However, as the heat generated from Joule heating is relatively larger than that of the endothermic reactions during charging cycling, the battery cell can still generate heat, with the amount of generated heat depending on the state of charge (SoC) and power flow of the battery cell [9]. By this condition, each battery cell in the battery module might carry a different performance and SoC, leading to different temperatures. Several studies have suggested that the different temperatures between battery cells must not exceed 5 °C [1,2]. Accordingly, battery thermal management systems (BTMS) are demanded to ensure the operating temperatures are within an optimal range and are well distributed across all the battery cells [10–12].

A BTMS, as a part of battery packing, has a role in maintaining the thermal condition of batteries under optimal conditions by performing heat transfer from the battery to the outside when the battery is prone to overheat, and occasionally vice versa when the battery is in a low-temperature application. Several prior studies have reported various developed BTMS designs and strategies, which can be categorized based on the working principle and the coolant material used to transport the heat. Under the working principle, the heat can either be transported by direct contact between the coolant and battery cell or by indirect contact through a pipe as a heat transfer medium (see Figure 1a) [13,14]. The significant factors influencing the thermal management performance of a direct contact BTMS are the battery pack geometry [15], the space between batteries [16], and the battery layout configuration [17]. When using a heat transfer medium, the significant factors that must be considered include the contact area [18] and pipe dimensions, such as height and thickness [13]. Both types also share some of the same significant factors, such as the coolant material [19], velocity [20], and temperature [21]. In the meantime, the coolant materials include air-cooled [21–23], liquid-cooled [24,25], and phase-change materials (PCMs) [26,27] (see Figure 1b). Each of these BTMS types have particular advantages and disadvantages. An air-cooled BTMS has a simple construction that makes it low-cost, but it still suffers from the low heat capacity of the air as the heat transfer medium.

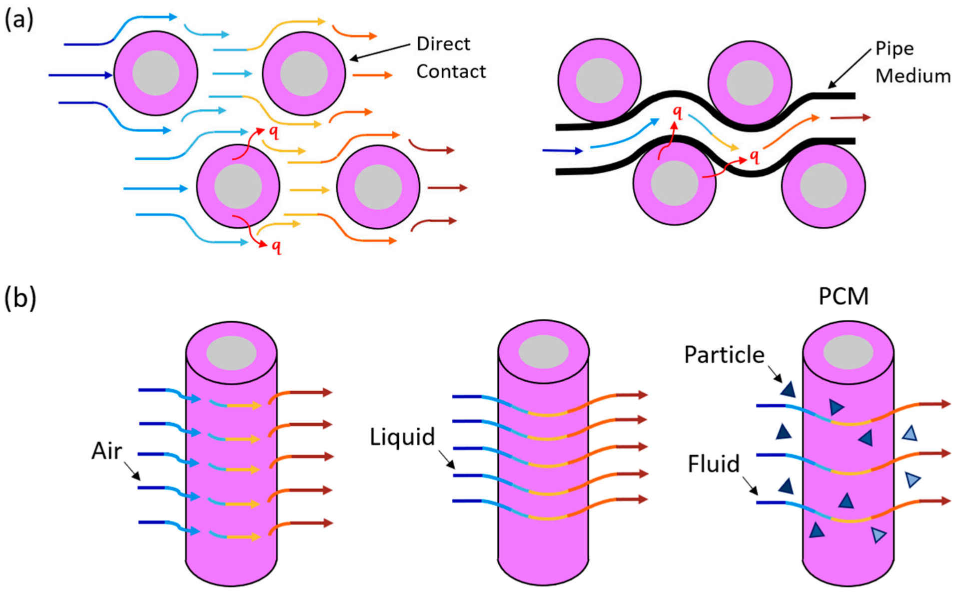

Figure 1. (**a**) Working principle of thermal transport from the battery to the environment and vice versa and (**b**) typical coolant materials for battery thermal management. The battery illustration only shows cylindrical cell types, but it also applies to prismatic and pouch cells.

On the other hand, a liquid-cooled BTMS utilizes liquid with a higher heat capacity than air, but practical EV applications require a high conductivity pipe, which leads to a complicated construction [21]. The pipe also possesses leakage risks and potentially prompts battery cell corrosion and short circuit. Subsequently, solid–liquid-phase-transitioning PCMs, mostly based on paraffin, have been developed to increase heat capacity and are widely suggested for EV battery cooling systems [28]. A PCM-based BTMS has a high efficiency and stable performance under extreme conditions due to its ability to store heat during the phase change process; however, the material has a low heat conductivity and needs to be regenerated after being completely melted [29]. Based on the working principle and the coolant materials used, more advanced battery packing design strategies have been presently proposed, such as air-cooled batteries with liquid cooling [30], liquid cooling with a heat pipe [31], and PCMs with a heat pipe [32]. For low-temperature operation, a preheating mechanism is utilized to initially condition the batteries under a working temperature. Preheating can be categorized into external preheating using air [33], liquid [34], or PCMs [35] and internal preheating using excitation by direct current [36], alternating current [37], and pulse preheating [38]. These strategies are applicable to different battery geometries, such as cylindrical, prismatic, and pouch, even though each type has its own thermal characteristics. Concretely, pouch cells tend to have maximum temperature near the terminal tabs due to the high concentration of local current densities. Cylindrical cells can have higher core temperatures than surface temperatures due to adiabatic conditions and higher thermal resistance at the cell core. In terms of thermal management, cylindrical cells have the advantage of a high heat transfer area, which can improve heat transfer by the BTMS. Prismatic cells also have their maximum temperature at their core and different temperatures across their thickness. However, in prismatic cells, the temperature rise might be mitigated by its large thermal mass. An additional fin also can be added in the case of prismatic cells to improve heat transfer by the BTMS [39,40]. BTMSs are expected to ensure that the battery temperature can be managed at optimal operating temperatures with a minimal temperature difference for each battery cell. In achieving the main objective of providing the optimal temperature and performance of LIBs, some challenges must be tackled in designing a battery pack. The advancement of LIB technology using different kinds of battery constituent materials that keep bringing higher energy density batteries must also consider thermal properties as an essential battery issue. The limited space of EV compartments for the battery and the BTMS is also the reason for the urgency of LIB packing technology advancement. The climates and seasons that vary in different places of the world and at different times of the year must also be considered as one of the battery packing design requirements. Furthermore, the safety of the battery, drivers, environment, and the BTMS itself must also become the main points of view in the design. This review paper provides a comprehensive discussion of the challenges, the recent advancement of technology, and the opportunities for research in the design and development of BTMS for EVs.

2. Challenges in Managing the Thermal Aspect of Batteries

2.1. Novel Battery Materials for Higher Energy and Power Density Demand

From 2008 up to now, LIB technology has been improved by an increase in the volumetric energy density to more than five times, with nearly a 90% cost reduction in the battery pack level. This substantial progress was achieved due to research and development in active materials, electrode processing, and cell manufacturing [41]. Early LIB commercialization was conducted by Sony in 1990 for electronic devices, in which a $LiCoO_2$ (LCO) cathode and a petroleum coke anode developed by the Goodenough and Asahi Kasei Corporation, respectively, were combined to create a fully rechargeable battery with an energy density of 80 Wh/kg and a volumetric energy density of 200 Wh/L [42,43]. The creation of LIBs with a graphite anode, proposed by Sanyo Electric, together with ethylene carbonate (EC) as the co-solvent in the liquid electrolyte based on Dahn's work, could increase the voltage and volumetric energy to 4.2 V and 400 Wh/L, respectively. For its increased oxidation stability, Guyomard and Tarascon published a novel electrolyte formulation, namely $LiPF_6$ in EC/DMC, in 1993 [44]. This electrolyte is still widely used today and allows LCO-based LIBs to have three times the energy density (250 Wh/kg and 600 Wh/L) of Sony's first-generation batteries [44]. Such an immense improvement is expected to be progressively performed for considerable opportunities in improving LIB technology [45]. Despite this, at present, the technology still cannot beat internal combustion engine (ICE) vehicles in terms of energy density.

Other cathode materials besides LCO have also been introduced for commercial EVs to ensure robustness and reliability during operation. They are $LiFePO_4$ (LFP), $LiNi_xMn_yCo_{1-x-y}O_2$ (NMC), $LiNi_xCo_yAl_{1-x-y}O_2$ (NCA) [46], $LiMn_2O_4$ (LMO) and $LiN_{0.5}Mn_{1.5}O_4$ (LNMO) [47]. Each cathode has superiorities over others. For example, LFP is considered the safest cathode but has the lowest energy density. LFP is usually used for low-cost EVs, light EVs, and electric motorcycles. LFP does not require a complex cooling system because it might not explode if a thermal event occurs [48]. In contrast, NCA has the highest energy density, but its explosive content requires a special battery packing design. Due to its characteristics, NCA batteries are used for luxurious cars requiring high energy and power densities. The safety issues are solved by implementing a more advanced BTMS, which might be expensive and complicated but reliable in their design. Furthermore, depending on its nickel content, NMC has moderate energy density and safety [49]. NMC-based batteries are suitable for heavy vehicles, such as electric buses and trucks, which require high density and moderate risk due to their size and the related implications when an accident happens. Spinel-type cathode materials, such as LMO and LNMO, were introduced as cobalt-free cathodes to counter the scarcity and toxicity of cobalt [50,51]. LMO cathodes are cheap and environmentally friendly but have a low energy density, making them less preferable for practical applications [52]. Nickel-substituted spinel cathodes, LMNO, known for their high voltage stability, have a high power-density and fast Li^+ diffusion [47,53]. On the other hand, the impurity of $Li_xNi_{1-x}O$ in LNMO drops the electrical performance, which makes the material difficult to prepare [54].

Significant work has been conducted by Murashko et al., in which they investigated the heat properties of LIB materials based on LFP, NMC, and NCA cathodes with graphite anodes. The specific heat capacity and thermal conductivity as a function of the SoC of the batteries were found to be different [55]. NMC and LFP have a higher specific heat capacity and a lower thermal conductivity, so they are more challenging to heat up and cool down, but this gives them more thermal stability. NCA, in comparison, has a lower specific heat capacity and a higher thermal conductivity. This means it is less thermally stable and is easy to heat up, but it is also easier to cool down. Such behavior needs to be accommodated by the BTMS to keep the LIBs in the optimal temperature range and with a minimum temperature difference.

In general, the higher energy density of LIBs results in a longer usage time, leading to more heat generation. The cooling load requirements for BTMSs are increasing along with the development of batteries with a high energy density. Different LIB constituent materials result in different heat generation rates and thermal properties. The main reason that NMC and NCA are more active than LFP is the adoption of nickel as the reactive material [49]. It might ensure high energy and power densities, but at the same time, it can easily generate exothermic reactions [56]. Golubkov et al. showed that NCA produced more flammable CO, CO_2, and H_2 gases than LFP during a temperature ramp test, indicating that NCA was more reactive than LFP [57]. The potential for flammable gas production is bigger when the SoC of the battery is full or overcharged. Table 1 shows a characteristic comparison of cathode materials generally used for EVs.

Figure 2 illustrates the heat flux curves during the charging and discharging processes of a common battery cell. During the charging process, the heat flux increases until a steady state value is obtained. The value depends on the charging rate. A steady-state condition is achieved when there is a heat flow balance among the environmental conditions, Joule heating, and endothermic chemical reactions during the charging process [58]. In contrast, rather than reaching a certain steady state value, the discharging process tends to generate heat in a transient manner [58]. The discharging process results in Joule heating and exothermic chemical reactions, which cause the heat flux to increase proportionally. Identical to the charging process, this heat flux also depends on the discharging rate. In the relationship of thermal management design, the charging process might implement a high charging rate as long as the steady-state heat flux does not cause a thermal event. For the discharging process, the heat flux can be limited by ensuring that the battery does not discharge with a high C rate in the long term. This condition can be controlled by the battery management system.

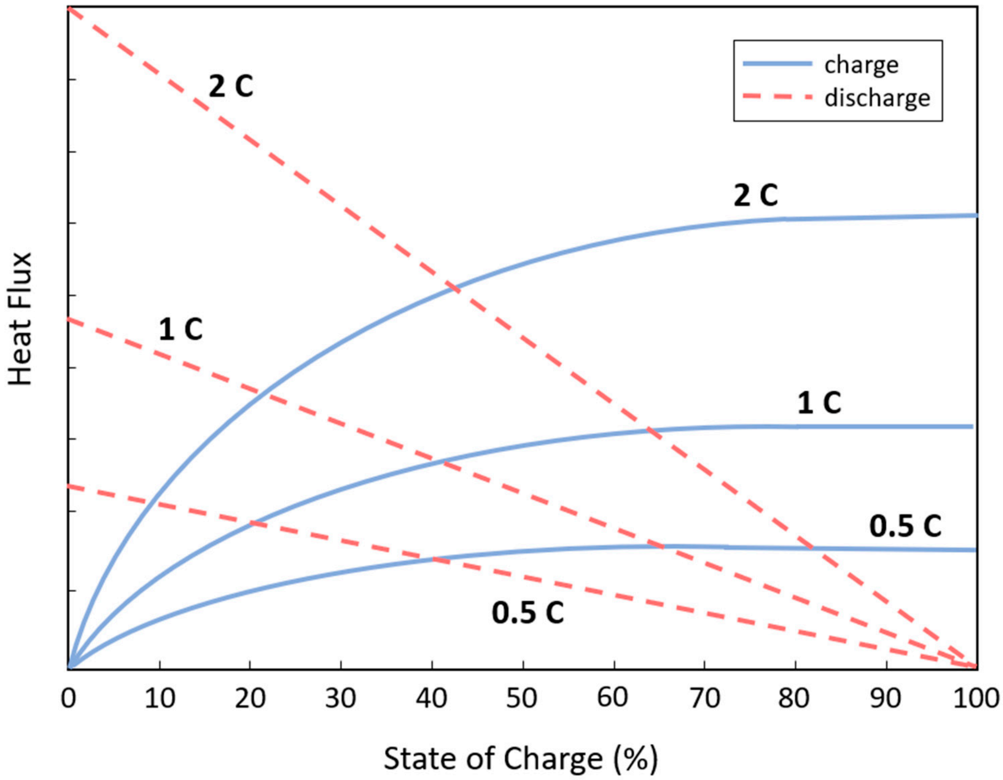

Figure 2. Typical heat generation curves of battery cells during the charging and discharging process.

Table 1. Characteristics of cathodes for lithium-ion batteries.

Cathode Material	Specific Capacity (mAh/g)	Average Potential (V, vs. LiO/Li+)	Max Discharge Current (A)	Acceptable Temperature (°C)	Refs.
$LiCoO_2$	140	3.0	8	0 to 50	[59,60]
$LiFePO_4$	95	3.5	70	−20 to 65	[61–63]
$LiNi_xCo_yAl_{1-x-y}O_2$	199	3.75	6	0 to 45	[64,65]
$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$	180	3.8	20	−5 to 50	[46,66]

2.2. Limited Vehicle Compartment Space and Safety

BTMSs of EVs need to have robust cooling and heating performances. This can be realized by increasing the system size to maximize the heat transfer area and the cooling medium. However, when designing the battery packing of EVs, we have only a limited space for the vehicles to work with ergonomically; hence, the design needs to be simultaneously as compact as possible and still sufficiently reliable. The limited space in EVs also makes the battery packs susceptible to heat accumulation, especially during fast charging and discharging [67]. Weng et al. showed that in a limited space with a limited cooling medium rate, increasing the heat transfer area does not always give a better cooling efficiency [68]. Indeed, a compact battery pack design is also required to ensure the high energy density of EVs and to compete with other vehicle types, such as ICE and hybrid vehicles.

Figure 3a shows the total carried energy versus the weight of commercial vehicles. ICE and hybrid vehicles are still leading in terms of energy storage. However, it is worth noticing that the efficiency of ICEs might be much lower (around 20%) compared with electric motors (about 80%) [69]. Furthermore, the efficiency of hybrid vehicles can be calculated based on whether the energy is stored in the fuel tank (20%) or the batteries (80%). Those efficiencies also depend on the power train configuration used for the vehicles [70]. A more complicated power train system requires more components, consequently reducing power train efficiency. Figure 3b shows the effective energy used for vehicles considering the energy efficiency of power trains. EVs still have lower energy storage, even though this is after considering the drive train efficiency. This problem is related to the battery's stored energy density, which is highly determined by active material characteristics and the heavy cooling system carried by the vehicles. Therefore, adding more batteries to EVs might not be beneficial, since this can increase the total weight of the vehicle. EVs have an advantage due to the use of electric motors having a constant torque in a wide range of rotational speeds, eliminating the transmission and gearbox. However, this advantage must be compensated by a heavy battery pack due to the low stored energy density. To compete with ICE vehicles, EVs must have at least a two times higher stored energy density than the current technology battery, as shown in Figure 3b.

Three common types of battery cells are available in the market that can accommodate the limited space for battery packing, namely cylindrical cells, prismatic cells, and pouch cells [71]. A cylindrical cell uses steel to wrap the battery with various diameters and lengths, which ensures full protection from mechanical loading [72]. The size is considerably small to ensure the battery cell has good thermal stability. The small size also helps the cell to be arranged within the available space. Furthermore, the small size also makes the cell adaptive to various battery modules or pack designs. However, these advantages must be paid with their low effective volumetric and gravimetric energy densities. In contrast, pouch batteries use aluminum polymer foils to wrap the cell [73]. This makes the cell have an effective high gravimetric energy density, but at the same time the strength and rigidity of the battery become questionable [74]. Such battery cells also require additional packs when they are used for EVs, reducing their densities. To improve the density, a prismatic cell is introduced with a relatively bigger size than other cells. This might be promising for EVs requiring a high energy capacity. However, their bigger size causes the cell to be not favorable for thermal management. The quality of each cell might also be different since it is more difficult to control the quality during the manufacturing process of these battery cells.

Besides the battery cell design, battery modules and packing are optimally designed to meet the available space and to provide good thermal management. The battery cells must unavoidably be arranged in series and parallel connections. A series connection is created to fulfill the required voltage, whereas a parallel connection is created to fulfill the required energy capacity [75]. In a series connection, the nonuniform charging/discharging process of each cell is unavoidable. Consequently, each cell has a different SoC, which implies different temperatures and different levels of Joule heating [76]. This phenomenon makes designing BTMS more complicated, which must be handled by optimized design strategies. It is worth noting that in designing battery packing, thermal management is only one of the main issues that must be handled. Other issues, such as vibration and crash safety, must also be considered during the design process [77].

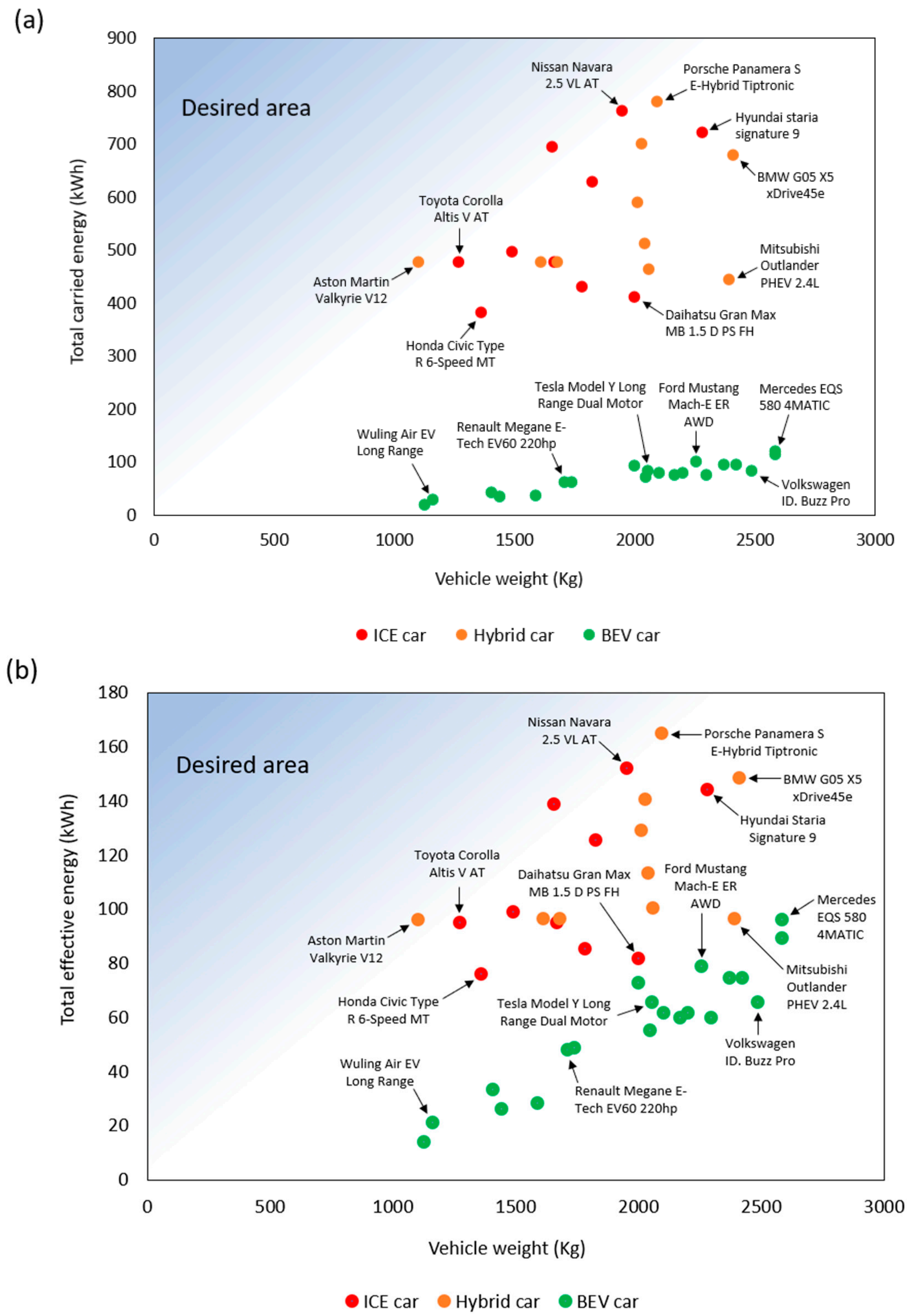

Figure 3. (**a**) Total carried energy by vehicles versus their weights and (**b**) total effective energy of vehicles versus their weights. The effective energy is calculated by considering total power train efficiencies of 20% for ICE vehicles and 80% for EVs.

2.3. Climate and Seasonal/Environmental Temperature

For obtaining the best performance and lifetime, LIBs should generally be operated at a temperature between 25 and 40 °C with a maximum difference between the batteries of 5 °C [1,2]. The optimum operating temperature might depend on the battery's active materials [78]. The battery's cooling and heating requirements should be considered depending on environmental conditions such as the climate, season, and driving circumstances. To improve the performance and maintain the battery's ideal state of health, the temperature across the battery pack should be kept inside the optimal range and as uniform as possible. As a result, a sophisticated BTMS with accurate temperature management capabilities in locations with varying temperatures throughout the year is greatly desired for EVs [79]. Since the heat transfer rate and specific heat of air significantly decrease during a hot summer, an air-cooled BTMS might not be suitable for year-round usage. An air-cooling system cannot provide the necessary cooling load to the battery pack [80]. A hot environmental temperature can trigger the battery to accelerate the redox chemical reactions, which directly causes an abundance of heat generation (thermal event). In the long run, the phenomenon can cause thermal runaway in the battery.

For subtropical climates, EVs require a heating system to ensure the battery does not freeze. A low temperature makes the battery lose its performance due to the increased liquid electrolyte viscosity, causing high internal resistance [81,82]. This makes the chemical reactions in the battery slow. As a result, the current output can be low, causing the electric motor of the EV drive train to not have the power to rotate. At an environmental temperature of 0 °C, the discharging capacity can drop by more than 20%, and the dropped capacity proportionally increases as the temperature decreases [83]. Even though a low temperature is usually less hazardous for a battery than a high temperature, the malfunctioning of the battery makes the EV unable to operate normally, which is less favorable than ICE vehicles. Figure 4 shows the effects of environmental temperature on battery performance for several battery types [84,85]. Operating the battery outside the optimal temperature causes low performance for both charging and discharging conditions.

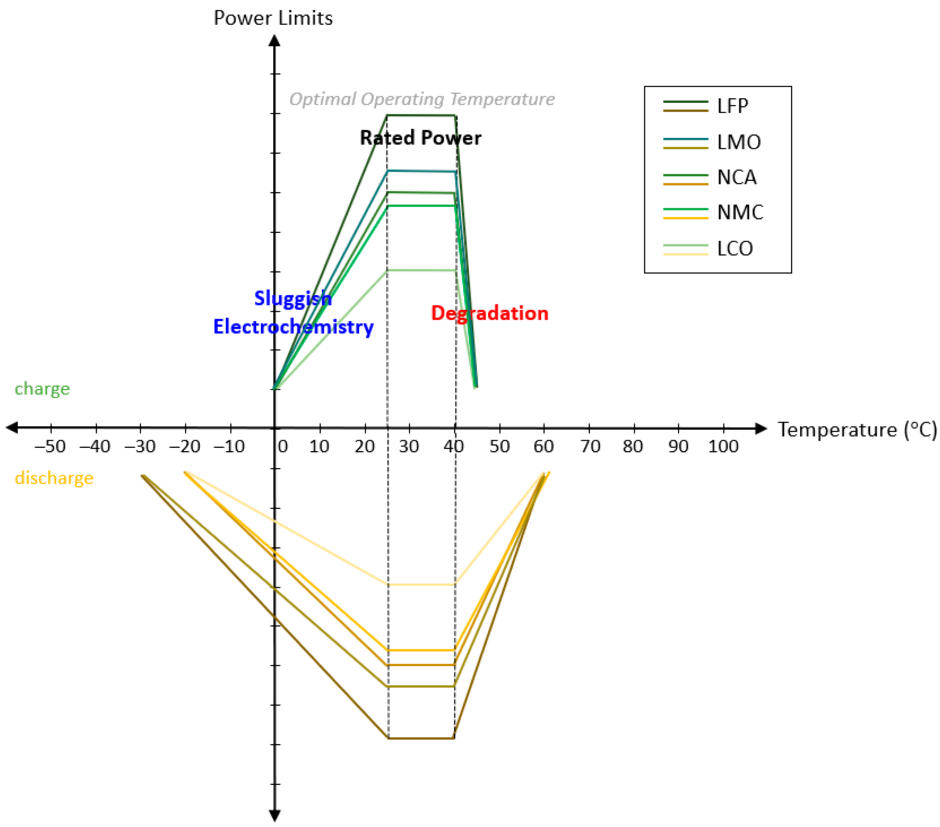

Figure 4. Typical LIBs performance during charging–discharging process for different temperature conditions.

3. Recent Advancements in Research and Development of LIBs

As a summary of the discussion in the previous section, three fundamental problems must be solved in designing battery packing with superior thermal management in EVs.

These problems have become design constraints that might be difficult to solve simultaneously. For example, considering the current technology of the constituent material of batteries, high-energy-capacity cathodes (NMC or NCA) release a lot of heat during the charging and discharging processes, increasing the thermal runaway risk [86,87]. Extreme climate or season conditions also require robust and complicated battery packing designs that might increase the vehicle weight and consume a lot of energy [79,88]. Optimizing a battery design that accommodates all constraints is usually suggested to solve such problems. In this section, we explain the significant findings from the recent decade that can solve these problems. Some ideas are still under ongoing research, which might become promising game changers in battery packing design and technology, even though they still need to be further proven before their implementation.

The thermal problems of LIBs, which are high heat generation and varying environmental temperatures, are caused by the narrow working temperature of LIBs. Recent advancements in battery technology give potential solutions to these problems, for instance by implementing a functional co-solvent for the electrolytes—or utilizing solid-state batteries. Functional co-solvents and electrolyte additives have been vastly studied and developed, with significant progress being achieved in recent decades such as in obtaining a longer cycle life, allowing a fast charging process, hindering electrolyte decomposition at the electrodes, enhancing the energy density, enabling a wider temperature range of operation, or producing lower-cost LIBs [89–95]. Lu et al. [96] proposed 2,2,2-trifluoroethyl N-caproate (TFENH) as a co-solvent for LIB electrolytes. The TFENH co-solvent improved the low- and high-temperature performance of a $LiCoO_2$/graphite battery by keeping the volume ratio of TFENH within 17 to 25 vol%. An X-ray photoelectron spectroscopy (XPS) test showed that a film of $CH_3(CH_2)_4COOLi$ was formed, which decomposed from the TFENH. The film reduced the other reduction reaction products from the carbonate solvent and lithium salt, which in turn improved the low-temperature performance and cycling stability of the LIB. Another co-solvent application was proposed by Ouyang et al. [97], which used a combination of fluoroethylene carbonate (FEC) and dimethyl carbonate (DMC) at a ratio of 3:7, named FD37. The co-solvent was used for an NMC LIB and showed a significant improvement in cycling features due to the formation of a cathode–electrode interface. The interface inhibited the electrolyte decomposition and further improved the stability of the electrode/electrolyte interface. The co-solvent also improved the thermal stability of the LIB, which was shown in high-temperature cycling and storage tests. The LIBs with an FD37 co-solvent showed a better capacity retention and Coulombic efficiency than the traditional LIB. However, employing this strategy in the LIBs with liquid-based electrolytes does not mean fully omitting the natural characteristics of liquid electrolytes that tend to have a consequence in easier fire ignition when it reacts with particular chemicals, even if they are non-flammable [98]. For small-scale applications, such as power sources for portable devices, attempting this strategy could be favorable and promising, while the drawback case might be conveniently handled or prevented. On the contrary, aside from the enhancement of the electrochemical performances required for large-scale demands, especially in EV applications, this technology needs more concern regarding safety, owing to the severe impacts, such as catastrophic fires or explosions, which will result in the case where the battery gets into trouble.

Therefore, in recent LIB development, it is believed that solid-state battery (SSB) technology could replace the LIB technology based on liquid electrolytes currently commercialized in the market, considering the exponential progress of SSB research pursued in the last decades, which is much improved compared to the initially revealed idea many years past [99,100]. Furthermore, a functional additive that previously accounted for significant advantages in LIBs could also be employed in solid electrolytes, allowing SSBs to become more promising candidates for next-generation power sources, especially for EV applications [101]. The use of materials such as oxide inorganic solid-electrolyte NASICON-type LATP ($Li_{1+x}Al_xTi_{2-x}(PO_{4})_3$), NASICON-type LGPS ($Li_{10}GeP_2S_{12}$), NASICON-type LAGP ($Li_{1+x}Al_xGe_{2-x}(PO_{4})_3$) or garnet-type LLZO ($La_3Li_7O_{12}Zr_2$) instead of liquid electrolytes with a separator enables the significant enhancement of a battery's capacity by up to four times due to generally of having a wide electrochemical stability window [102]. The main capacity of LIBs is in the range of 150–200 mAh [103]. Liu et al. recently constructed a solid-state Li–air battery with lithium foil anode, LAGP and a solid electrolyte, and an LAGP–nanoparticle composite/single-walled carbon nanotubes (SWCNTs) as the air electrode [104]. A remarkably high capacity of 2800 mAh/g was shown in the first cycle despite the good cycling performances being limited to 1000 mAh/g, and the electrochemical process may vastly differ between an air and a pure oxygen atmosphere. Tao et al. reported that the use of LLZO-nanoparticle-filled poly(ethylene oxide) electrolytes could generate favorable capacities of >900, 1210, and 1556 mAh/g at successive temperatures of 37, 50, and 70 °C, respectively, even though at the first charge/discharge cycle they ran into an irreversible electrochemical reaction, which lead to capacity decay [105]. Accordingly, the use of solid electrolytes also allows the battery to have a wider operational temperature owing to the high thermal resistance, and this substantially increases the battery safety significantly, even in harsh environments [105–109]. The current method proposed to extend the temperature range is thus available by coupling the types of solid electrolyte material and implementing such filler/substitute material. These superiority aspects lead SSBs to be the primary candidates for solving the low-density and safety concerns that mostly arise in conventional batteries. Furthermore, the manufacturing process of SSBs can be considerably easier when producing a solid electrolyte using additive manufacturing, spark plasma sintering, or conventional sintering [106]. The installation of solid electrolyte in SSBs could also prevent leakage that commonly arises from the liquid electrolyte, which can cause a short circuit and thermal runaway [107].

The promising nature of SSBs does not mean they can be implemented immediately. In fact, one remaining fundamental problem must be solved, i.e., mechanical damages that always appear after several charging–discharging cycles [108]. These damages occur due to the solid electrolytes that always bear the pressure loading from the expansion–shrinkage of electrodes, which is different to liquid electrolytes that can redistribute the pressure around the cell pack. The most common solutions to avoid these damages involve using zero-strain cathodes such as LTO or limiting the SoC in the battery application to ensure the solid electrolyte is not subjected to overpressure. The high internal resistance of SSBs also occurs due to the low quality of the manufacturing process. Toyota has spent research funding to solve the SSB problem so that they can be implemented in their cars [110]. Bolloré Group launched the BlueIndy electric-car-sharing program to demonstrate an EV prototype installed SSB of 30 kWh [111]. Other established companies such as Volkswagen, BMW, Daimler, and Hyundai also keep paying attention to the research and development of SSB technology [112]. The immediate solution to overcome the high heat generation of high-energy-density batteries and their environmental problems is through advanced BTMSs, which have better thermal management performances. The advancement of BTMS research has resulted in hybrid BTMSs, which combine one type of BTMS with another to utilize the advantages of both systems while overcoming the weaknesses of each system. Yang et al. [30] combined mini-channel liquid and air cooling to improve the BTMS cooling performance for cylindrical batteries. The maximum temperature and temperature distribution were reduced to 2.22 and 2.04 K, respectively. Another hybrid BTMS combining liquid cooling with a heat pipe was proposed by Jang et al. for a prismatic battery [31]. The liquid cooling utilized a mini-channel heat sink placed on top of the battery, while a heat pipe was placed on the front side of each battery. The heat pipe transferred the heat generated by the batteries up to the heat sink area to be further transferred by the liquid coolant out of the battery pack. The proposed BTMS successfully reduced the maximum temperature of the battery up to 9.4 °C. A BTMS with a combination of a liquid PCM and a heat pipe for a pouch battery was proposed by Zhou et al. [32]. The PCM took the heat from the battery through convection, and then the heat pipe transferred the heat out of the battery pack by air. The system lowered the temperature difference between the batteries by up to 67% compared to a forced air-cooled BTMS. A comparison of several of the recent

BTMSs is presented in Table 2. The progress of BTMS strategies in providing the optimal temperature conditions of batteries with a maximum temperature of 25 to 40 °C and a maximum temperature difference of 5 °C, which LIBs require, is summarized in Figure 5.

Table 2. BTMS comparison.

BTMS	Maximum Temperature (°C)	Maximum Temperature Difference (°C)	Refs.
Air-cooled (AC)	34	4.4	[22]
Liquid-cooled (LC)	37.36	1.96	[24]
Heat pipe (HP)	31	4.6	[20]
PCM	44.5	0.42	[26]
Air–liquid-cooled (AC/LC)	29.61	2.09	[30]
Liquid-cooled heat pipe (LC/HP)	24.6	4.27	[31]
PCM heat pipe (PCM/HP)	48	2	[32]

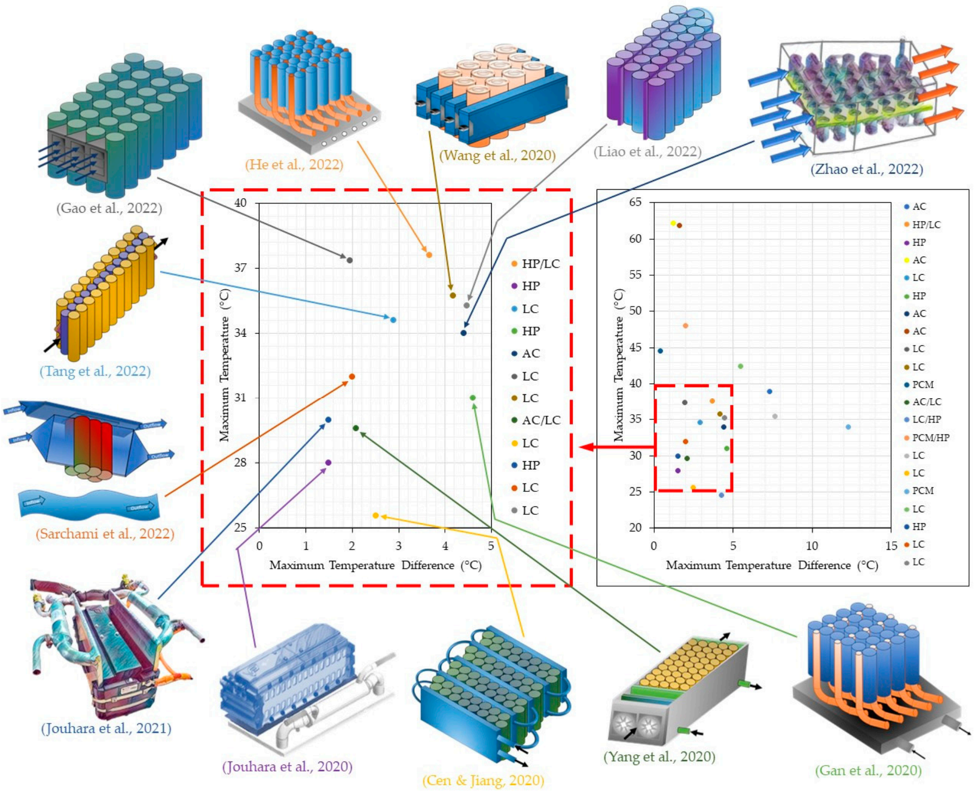

Figure 5. The progress and achievement of BTMS strategies in providing the optimal temperature conditions for LIBs in the form of AC [7], HP/LC [13], HP [14], AC [15], LC [18], HP [20], AC [22], AC [23], LC [24], LC [25], PCM [26], AC/LC [30], LC/HP [31], PCM/HP [32], LC [67], LC [80], PCM [113], LC [114], HP [115], LC [116], and LC [117].

The mentioned research [30–32] proved that hybrid BTMSs could improve the cooling performance of ordinary BTMSs. However, the drawback of hybrid BTMSs is that they require a higher energy consumption and a bigger compartment space. Therefore, due to their compactness (handling the limited compartment space) and minimum power consumption, without sacrificing safety, direct-cooling BTMSs have been introduced in the last decades [80]. Their cooling design is superior to air- and liquid-cooling designs. In addition, they can be integrated with the air conditioning system of an EV to achieve a compact design without sacrificing the cooling performance [113,118,119]. The basic idea of direct cooling BTMSs is that the battery requires an operational temperature similar to the comfort temperature of the passenger. Thus, the cooling system of the battery and cabin can be integrated. A direct cooling system solves the basic problem of air-cooling system, which is usually unreliable without implementing a complicated structure, such as liquid cooling. Together with an advanced control system, direct cooling BTMSs could be promising for solving the thermal management of EV batteries. At this time, the Nissan Leaf and Toyota Prius use a direct cooling system and show favorable performance.

A battery preheating mechanism was a method introduced and proposed by researchers for EV applications in cold environmental temperatures, which can be further categorized into external and internal preheating. External heating uses a heat source outside the battery to heat the battery by transferring the heat through a medium, such as air, liquid, or PCM. Air preheating uses power from the battery to heat a resistance heater and then transfers the heat to the battery via air convection produced by a fan [33]. In contrast, Wang et al. [34] proposed an immersive preheating system by immersing prismatic batteries in a flowing heat transfer liquid. The system used an external heat exchanger to heat the liquid for heating the battery. Ruan et al. [36] proposed an internal preheating method by direct current discharge due to its simplicity and high heat generation. The research successfully optimized the heating time to 103 s and reduced the capacity degradation to 1.4%. Zhang et al. [37] proposed a preheating mechanism using a sinusoidal alternating current, causing the battery to be only heated by the irreversible heat of Joule heating, since the reversible heat of the electrochemical reaction was canceled out after one period. The study found that the heating process can take less than 15 min with no capacity loss after repeated preheating, which was slower than DC preheating but had less capacity degradation. Moreover, a pulse internal preheating system heats the battery by pulse excitation, which Wu et al. [38] successfully optimized by varying the amplitude and frequency. The results showed that the heating time was 308 s with a capacity degradation of 0.035% after 30 cycles.

Advanced control systems always become the main solution to control complicated BTMSs, considering that heat generation in the battery caused by internal resistance (Joule heating) and redox chemical reactions cannot be avoided. The same thing also goes for the non-uniform temperature of each cell, which is also unable to be averted since the battery must be arranged in both series and parallel connections. Hence, a control system was implemented to ensure a constant and uniform battery temperature, which can be approached by two methods. The first approach is to control the SoC and voltage level of each cell using a battery management system (BMS) so that the battery can generate heat uniformly.

In addition, a BMS can also restrict the excessive current flow during the charging–discharging process, which commonly raises the heat generation drastically. The second approach is installing a temperature sensor, heat flow sensor, fuse, and gas sensor for identifying a heating spike. The data obtained from the sensor can then be analyzed to determine the necessary action of a cooling system set. The development of machine learning in this situation can plentifully help researchers to find robust control systems that are urgently needed, especially for extreme climates and weather. Figure 6 maps the efforts conducted to solve the thermal management issues, and it can be seen that many solutions have been proposed to tackle the thermal management issues. However, the facts show that the researchers are only capable of dealing with it partially. This implies that thermal management issues are still the biggest concern, which is directly related to the main safety concerns of EVs, aside from the driver's range anxiety.

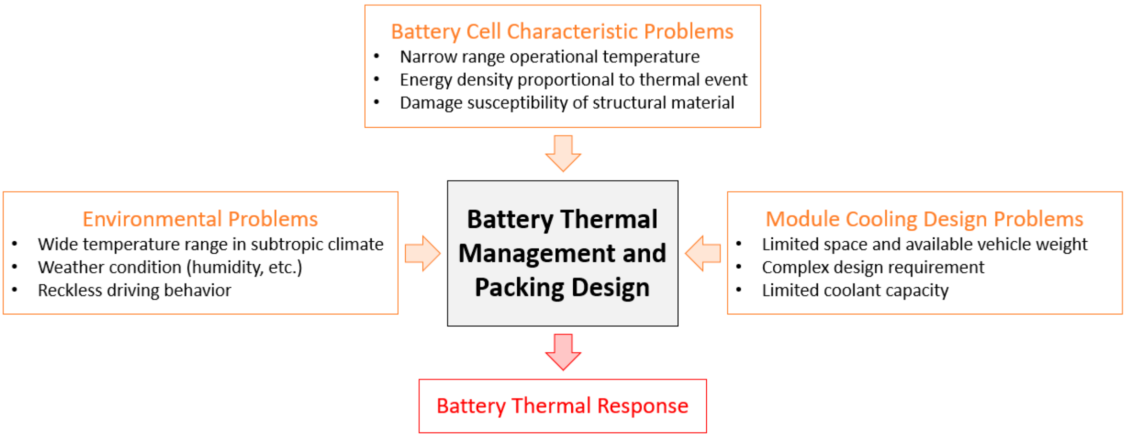

Figure 6. The remaining problems of battery thermal management and packing design that must be solved in future research.

4. Future Perspectives of BTMS Design

In recent decades, a great deal of research has been devoted to preventing thermal events and thermal runaways in batteries, which practically bears out the fundamental problem of EVs. Various proposals of solutions to ensure a constant, steady, and uniform operational temperature were introduced and substantiated to resolve these problems, regardless of the limited and controlled conditions encountered, such as in lab-scale or prototype models. Consistent progress drawn from these conditions is expected to lead to further research opportunities until a superior battery thermal management is realized for general application.

To systematically discuss and analyze the recent progress and future prospects of thermal management in the battery packing of EVs, we divided the solutions into two main categories: practical and fundamental solutions. The difference between both solutions is in how they define the problem and propose solutions in terms of complying with the thermal management requirements of battery packing design. In practical solutions, the researchers strive to develop advanced module cooling strategies to ensure the battery cells are at operational temperature and has a low temperature difference among its battery cells. Significant efforts have been deployed to address this concern. In contrast, fundamental solutions focus on improving the battery cell to resist environmental conditions and thermal self-generation (see Figure 6).

Under practical solutions, the ongoing research on battery management technology is presumably capable of reaching maturity, which can be implemented in future EV design. Some promising technologies have been developed, including the implementation of machine learning for advanced control systems [114,120], high thermal diffusivity fluids by nanofluids for liquid coolants [121], and reconstructions of battery packing to obtain the temperature distribution among the cell levels in a compact design [115]. Tang et al. implemented machine learning to analyze the performance of liquid-cooled batteries [120]. Implementing machine learning can predict cooling parameters that can significantly improve the liquid-cooling performance without expensive and time-consuming experiments. Another significant piece of work has been conducted by Khan et al. who implemented and developed machine learning to optimize the design of liquid-cooled thermal management in a battery [114]. These studies proved that machine learning could effectively increase the liquid-cooling performance in the design process and operation.

Nanofluids are another promising method for further improving the cooling capacity by altering the thermal transport properties of the cooling liquid. Nano-sized solid materials, mainly metal oxides and carbon nanotubes (CNT), with superior thermal transport properties can be mixed into the liquid to improve its thermal transport properties. Dielectric liquids (aliphatic liquids, silicone liquids, fluorocarbons) and non-dielectric liquids (water, ethylene glycol, oils) have been used as base fluids to combine with nanoparticles to improve heat transmission. The fluid's poor thermal conductivity determines the heat transfer rate, a problem for well-known heat transfer fluids including water, glycol, and oil. Mixing nanoparticles into these fluids is one of the most acceptable ways to boost their thermal conductivity. An essential step in nanofluid research is preparing the fluid to produce a stable fluid that will not agglomerate at high temperatures or after a specific time. Nanoparticle agglomeration is a fundamental issue with all nanopowder technologies that needs to be addressed in order to produce effective nanoparticle suspensions. The creation and suspension of non-agglomerated or uniformly distributed nanoparticles are necessary to significantly improve the heat transfer properties of nanofluids.

A number of experimental and numerical studies have been reported on the thermal conductivity of nanofluids as a function of temperature, volume fraction, nanoparticle properties, size, and shape. An experimental study with an improved cooling efficiency has also been reported for the water cooling of a battery pack by adding alumina nanoparticles to water as a base fluid [116]. With a relatively low volume fraction of aluminum oxide at 2 vf%, an increase in the heat transfer coefficient was observed, resulting in an enhancement of the maximum temperature and temperature difference by 7.76% and 117.668 and 0.26 K, respectively [116]. Aluminum oxide with a much higher thermal conductivity could increase the overall thermal conductivity and density of nanofluids, improving the heat transfer rate of the cooling liquid [122]. A numerical simulation of a liquid-cooling BTMS for 31 lithium-ion batteries reported a maximum temperature difference decreases of 12.6% by employing Cu–water-based nanofluids [117]. The simulation results also showed a proportional effect of the cooling performance as the volume fraction increased to 5%.

However, the addition of nanoparticles in the cooling liquid increases the density of the liquid, affecting the pressure drop along the liquid flow. A higher pressure drop requires more powerful and expensive pumping equipment, reducing the overall battery performance. At a low Reynolds number of 920, the pressure drop increased significantly to over 60% at a 2 vf% nanoparticle addition [116]. A lesser effect of nanoparticles on the pressure drop was shown with a high Reynolds number of 1840, generating only 8.33% of additional pressure drop with 2 vf% of nanoparticles [120]. In summary, nanoparticle addition in cooling liquids in the form of nanofluids may boost the cooling efficiency, which is a promising practical solution for BTMSs. The addition of nanoparticles is, however, limited by the dispersion conditions in the liquid and the operational flow characteristics, which determine the effects of nanoparticle addition on the pressure drop.

The reconstruction of more robust battery packing is also one of the practical solutions to handle battery packing design problems. Arora et al. show that for commercial cars, relative battery cell movement and displacement are commonly used as the failure criteria of the packing. The source of movement or displacement can come from a thermal event, vehicle vibration, or impact loading when an accident happens [77]. Most cars position battery packs integrated into the chassis to ensure they can have sufficient structural rigidity and be protected from front, back, and side impacts. Another common method is rearranging the battery cells to achieve the most efficient space usage without sacrificing thermal management. Many studies have proposed cell arrangements for cylindrical battery cell types, including inline or staggered formations, a number of series and parallel connections, and customized cell sizes.

Furthermore, the arrangement can only be focused on the cell size and geometry for other types of battery cells since they can be more flexibly arranged. An innovative battery pack is demonstrated by Tesla, in which their battery packs in their cars use a small wire fuse to protect the battery cells from thermal events [123]. The Nissan Leaf considers using direct cooling rather than liquid cooling to manage the battery temperature. It is worth noting that even though the practical solutions might work for actual applications considering the currently available battery technology, they still require complicated design and manufacturing processes, which might not be economically beneficial for commercial cars. Each implemented battery pack technology must be tested and proven safe, following standards, to have a high reliability and, simultaneously, not significantly increase the manufacturing costs to compete with ICE cars. A permanent solution that solves the fundamental problems of battery management systems has to be found as soon as possible.

To overcome the fundamental problems, the characteristics of non-flammable designs, -wide-range operational temperatures, and non-poisonous materials must be unveiled in the future by conducting research and development. The material couple of anode–electrolyte–cathode also ought to have low Joule heating and low heat generation considering the internal resistance and redox chemical reactions. SSBs have been admitted as a permanent solution to tackle the low mechanical stiffness and battery strength induced by liquid-based electrolyte use. In addition, SSBs can produce wider operational temperatures. As studied by Ogawa et al. [124] solid-state thin film lithium batteries can be operated at a low temperature of –40 °C with a high temperature of 170 °C, and, correspondingly, a recent study from Wang et al. [125] showed that lithium-metal-based SSBs can be operated at the temperature range from −73 to 120 °C. Using solid materials to replace flammable organic liquid-based electrolytes would also allow the battery to resist thermal events [126]. Furthermore, the possible much lower freezing point could make SSBs operate at a lower temperature, making them more promising and capable of running in subtropical climates [127].

However, as discussed in the previous section, the mechanical damages of SSBs must be initially solved, such as by implementing functionally graded material (FGM), which is currently predicted as one solution that can solve this problem by eliminating the thermal management component in the battery packing [128].

SSBs with future ideal materials make it possible to integrate battery cells into the EV frame or body [129,130]. This idea can be a game changer in which the battery will also become a load-bearing structure. This would be possible if a novel multi-functional material that not only stores energy but also acts as a load-bearing structure could be found. At this stage, the voltage and capacity of the battery can be achieved by one cell only, in which the design of the series and parallel connections of the battery is not required. This proposed research topic can possibly and interestingly be further explored, but it would still require much groundbreaking research to be conducted before implementing this technology. In other words, all this SSB research is still on the laboratory scale and probably needs time to be ready and to be implemented in EVs.

5. Conclusions and Recommendation

This paper reviewed the fundamental problems of BTMSs in EVs. The design strategies of battery packing to solve these problems were also explained comprehensively. It was shown that many research publications have tried to analyze and summarize the strategies for solving these problems. Finally, complicated battery packing, including advanced control for thermal management, was introduced to ensure that the battery cell temperatures are kept at optimal operating temperatures. This is a practical solution due to the current state of battery technology.

Thermal management systems might not be required in the future after novel material constituents of batteries are found. The new materials should possess the properties of being non-flammable, having a wide-range operational temperature, being non-poisonous, and generating low Joule heating and redox chemical heating. In fact, the current battery operating temperature is identical to environmental temperatures, which might not require additional battery temperature control as long as novel material constituents are found. SSB types of battery are believed to be the next generation of battery technology for EVs. Furthermore, materials that can be used for the EV frame are also desired, which means that they must be able to bear external loading.

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