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Calorimetric methods and thermal management of lithium-ion batteries: A mini-review

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Abstract. Lithium-ion batteries can be employed in various applications, including grid integration, electric vehicles, grid support, and consumer electronics. Lithium-ion batteries are currently one of the most important options for storing electrical energy. Therefore, modelling lithium-ion batteries and examining their temperature distribution and heat transfer using different calorimetric techniques is very important mostly for safety concerns. Thus, the study of battery heat transfer helps designers to propose and develop a suitable cooling or thermal management system. Different sources including overpotential contribute to heat generation. Different understandings were achieved from the previous modelling and experimental studies which involve the necessity for more accurate heat generation measurements of lithium-ion batteries, and improved modelling of the heat generation specifically comprehended at large discharge and charge rates for different applications including electric vehicles.

1. Introduction

Lithium-ion batteries (LIB) are being used as electrochemical storage in different applications, via which energy could be stored in the configuration of potential chemical diversity and utilized on every occasion required. LIB have acquired much consideration from researchers worldwide. Purely electric vehicles, hybrid electric vehicles, and plug-in hybrid vehicle advancements are currently the focus of the research activities of almost all automotive companies. Notwithstanding, LIB could have a more significant role in the twenty-first century, especially as an essential ingredient for advancing energy sustainability and the energy transition to renewable energy supply.

Chemical reactions occur inside lithium-ion batteries. Battery calorimetry can be used to measure the heat generation data during the charging and discharging process of LIB. Quantitative data on heat generation is needed for optimum safety and performance under every condition. The heat generation data from battery calorimetry is required for battery thermal modelling and the design of proper thermal management systems. Many studies have been accomplished on the thermal modelling of LIB but less attention was paid to the battery calorimetry methods for that purpose. Therefore, the main objective of this study is to review the calorimetric methods and thermal modelling of lithium-ion batteries. The operating temperature of LIB is one of the most notable features affecting both the lithium-ion battery pack's performance and lifespan. The LIB designers should understand lithium-ion batteries' thermal characteristics to sketch a thermal management system for lithium-ion battery packs. Thermal analysis and in-depth characterisation of LIB can help to develop a precise thermal model and to design an efficient thermal management system. Notwithstanding, there is often only partial or no knowledge of the chemical composition of commercial lithium-ion batteries, which makes the modelling a challenging task. A thermal management system for lithium-ion batteries to hold the temperature at a specific ideal range is indispensable for numerous applications of lithium-ion batteries, in particular, electric vehicles, to assure working safety.

Liu et al. [1] overviewed the problems in the field of battery thermal management and finally examined the existing methods for solving these problems, including thermal problems. Ling et al.[2] reviewed the thermal management methods of photovoltaic cells and lithium-ion batteries. Rao et al. [3], as well as El Nisilo et al.[4] accomplished an overview of research in methods and materials employed in thermal management of power sources employed in electric, hybrid, and fuel cell vehicles. Wong et al. [5] published a review article on thermal management and life expectancy models for lithium batteries in automotive applications. The paper's thermal management system strategies have been air-cooled fluid, phase change materials, and heat pipe. Xia G et al. [6] reviewed different battery thermal management systems in electric vehicle applications. Wang et al. [5], and Malik et al. [7], examined the different types of batteries and electric vehicles produced by different companies. Finally, they studied the importance of thermal management and its methods.

Diminishing the time needed to charge or discharge lithium-ion batteries is an essential goal in expanding zero-emissions vehicles. In addition, it can assist autonomous vehicles such as electric buses in decreasing expenses and working downtime. The lithium-ion battery produces more heat during rapid charging and discharging conditions. This heat should be transferred rapidly to avoid a rapid increase in temperature in the lithium-ion battery. Understanding the thermal behaviour of lithium-ion batteries, specifically during rapid charging and discharging cases, is crucial. Unfortunately, less attention was paid to this subject. Different approaches were demonstrated to model the non-homogeneity of the lithium-ion battery cell temperature. By modelling and simulating heat loss and lithium-ion batteries' thermal behaviour, temperature gradients of lithium-ion batteries at different current rates could be determined which helps to develop a well-adapted thermal management system.

2. Calorimetric Methods

Lithium-ion batteries can help incorporate wind energy and photovoltaic in the energy combination by supporting storage capacity. Besides, lithium-ion batteries could be used in off-grid energy supply systems, including solar house systems, to help access electricity in growing areas. Today, with the development of electric cars, hybrids, phones, and tablets, the use of lithium-ion batteries with high storage volume is required. Electrified vehicles such as hybrid electric vehicles, fuel cell hybrid electric vehicles, and electric vehicles; are needed to reduce carbon dioxide emissions. [8,9].

Thermal analysis of lithium-ion batteries using experimental data from battery calorimeters is critical because these LIBs would substantially rise in the temperature and heat loss gradient throughout charging and discharging in an actual application, mainly as a consequence of the irreversible and reversible heat. Thermal analysis and LIB heat measurements are required for cost-effective and safe electric vehicles with a large driving range. Several sources contribute to heat generation inside LIB comprising different causes of overpotential as irreversible heat sources, reversible heat sources, the heat of mixing, and the heat of phase change. These are illustrated in Figure 1.

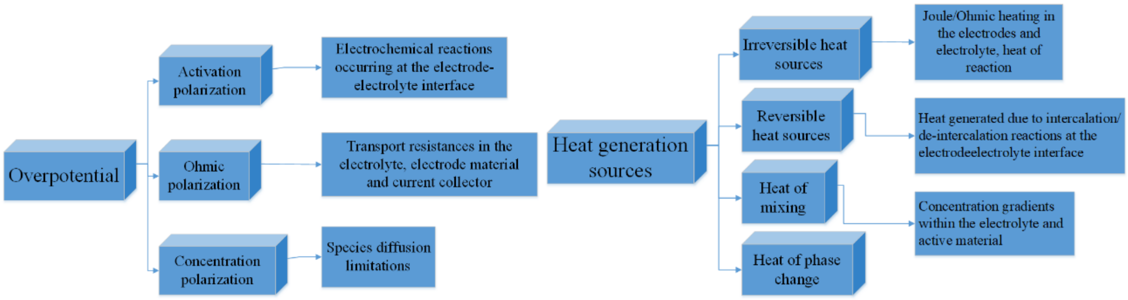

Figure 1. Different causes of overpotential and different sources contribute to heat generation [27].

The overpotential is explained as the variation between the battery cell's theoretical open circuit potential and operating potential. It characterizes system irreversibility and usually has the most significant influence on heat losses. The overpotential between the open circuit potential and the operating potential of the LIB results in significant polarization. While lithium ions overcome the resistance at the interface for their deintercalation and intercalation, heat is generated. Reversible entropic heat or entropy variation is another critical parameter. Entropic heat is heat generated in the reversible process, which originates from the reversible entropy variation throughout electrochemical reactions. Further irreversible processes can generate heat, comprising the ohmic heating process, active polarization process, and heating attributable to enthalpy change and mixing. In an efficient and homogeneous process, it is frequently challenging to relocate the heat generated throughout rapid charging attributable to resistive heating. Temperature inhomogeneity both on cell and pack levels causes safety concerns and accelerated degradation. Enthalpy variation is a form of an irreversible process that produces heat. Enthalpy variation occurs due to phase changes in the cathodes. When LIB are in the discharging or charging process, the ion distribution turns out to be inhomogeneous, which could cause heat generation through the mixing of ions. The ohmic heating process appears in the electrolyte and the electrode [10,11].

Calorimetry was employed by different researchers for heat generation measurements of LIB [12-16]. Kazuo Onda et al. [17] studied experimentally the heat generation behaviour of small lithium-ion secondary batteries. The heat source conditions to enhance a small lithium-ion battery's temperature, including the entropy alteration and over potential resistance, were measured through different approaches. Besides, the lithium-ion batteries' total heat generation and temperature rise were determined. Javad Esmaeili et al. [18] developed heat source terms containing heat loss at rest conditions for lithium-ion battery packs by employing up-scaling information from the cell scale. Yo Kobayashi et al. [19] carried out a combined electrochemical-calorimetric measurement on a spinel lithium manganese oxide cathode and graphite anode lithium-ion cell. The irreversible thermal behaviour recognized by calorimetry demonstrated the degradation of lithium manganese oxide at high temperatures. R. Cohen [20] investigated the influence of different parameters such as storage, depth of discharge, and current density on the Coulombic efficiency and heat generation rate of different cells. Various commercial cells from different manufacturers were tested. It was found that the Coulombic efficiency for the two arrangements was considered significant even at enormous temperatures and high current density. It was concluded that the heat factor, which was the proportion between the useful thermal energy and the electric energy produced by the cell, was approximately identical for different cells. D. F. Untereker [21] investigated the thermal behaviour of different battery technologies. They have employed electrochemical calorimeters to specify electrochemical reactions, electrodes, and cells' behaviour. An uncomplicated model for comprehending calorimetric information from the lithium-ion battery during discharging was established. Calorimetry has been recommended as an approach for quantifying self-discharge rates. Can-Yong Jhu et al. [22] studied thermal abuse behaviour, including thermal explosion hazards about adiabatic runaway reactions in commercial lithium-ion batteries, which were investigated by employing an adiabatic calorimeter. It was found that charged LIB was more hazardous compared with uncharged batteries. Hui Yang [23] determined the irreversible and reversible heat of a cell using the electrochemical-calorimetric approach. Frank B. Tudron [24] determined the thermal factors of a cell under different circumstances of constant load. A thermodynamic computation was accomplished by providing a statement expressing the heat development rate produced through a tiny battery cell under load to the current applied to the cell. Madani et al. [25] determined the heat loss of a lithium titanate oxide battery under fast charging conditions. The working temperature of the lithium-ion battery was assumed to be 20 °C. The general evolution of heat losses throughout charging from 1 C to 8.5 C was a moderate growth for a working temperature of 20 °C. The increase in heat loss turned out not to strictly follow the increase of the current level. The heat loss began from 6986 J for 1 C and then underwent an average increase from 1 C to 8.5 C showing growth by a factor of six. The most striking alteration was from 7 C to 7.5 C charging, which grew by 13% compared to 7 C. G. Vertiz [26] employed experimental and calculated approaches to characterize the heat generation of a commercial large-size pouch cell. In addition, the values from the experiments were compared with the heat generation estimated by the Newman model.

Figure 2 shows seven calorimeter types. In an isoperibolic calorimeter (s. Figure 2(a)) the temperature of the calorimeter walls is kept constant and the sample temperature changes with time r.

Thermal resistance is defined by measuring the sample temperature change and temperature of the calorimeter walls. In the contrast to isothermal calorimeters (s. Figure 2(b)) both the temperature of the calorimeter walls and the sample temperature are kept constant. In addition, thermal resistance is very small. The third type is an adiabatic calorimeter (s. Figure 2(c)), where both the temperature of the calorimeter walls and the sample temperature change with time. In addition, thermal resistance is very big, which means that the cell cannot transfer heat to the walls. In a Tian Calvet heat flux calorimeter (s. Figure 2(d)) the difference between the temperature of the calorimeter walls and the sample temperature is held constant and the heat flux is measured. In Figure 2(e)-(g) three subtypes of the adiabatic calorimeter are shown, namely the Accelerating Rate Calorimeter (ARC), the bomb calorimeter and the reaction calorimeter. Both the bomb and the reaction calorimeter can be used to investigate thermal stability and chemical reactions on the level of the materials, whereas the ARC allows to performance of thermal abuse tests on the cell level and study the related thermal runaway reactions.

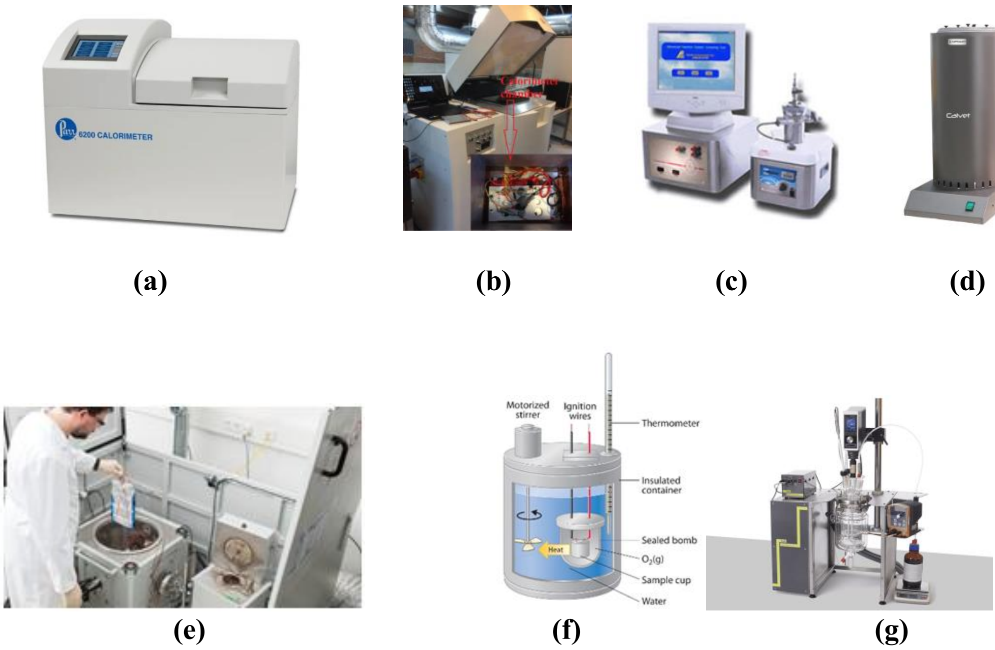

Figure 2. (a) Isoperibolic calorimeter [28], (b) Isothermal calorimeter, (c) adiabatic calorimeter [29], (d) Tian-Calvet heat flux calorimeter [30], (e) Accelerating rate calorimeter, (f) Bomb calorimeter [31], (g) Reaction calorimeter [32].

A thermal model and a thermal management system were developed for lithium-ion batteries by using battery calorimetry. The methodology scheme is illustrated and described in Figure 3. A dual potential multi-scale multi-dimensional battery model from ANSYS was used. A method was employed to simulate and model a lithium-ion battery's thermal behaviour at different environmental temperatures and current rates. The three-dimensional temperature profile of the cell was estimated. The investigated models made it feasible to notice and display the discernible heterogeneity of the lithium-ion battery's surface temperature distribution at different current rates. This research employed a second-order equivalent electrical circuit LIB model. The equivalent circuit model parameters were specified from multi-pulse discharge and charge data. Calorimetric tests were done to support the modelling approach. By employing the heat loss, which was determined by the isothermal battery calorimeter, the obtained model was simulated to determine the temperature distribution [33]. In the modelling, groups of equations were developed to explain the lithium-ion battery's dynamic response and performance. In addition, heat generation and electrical models were used to create a dynamic thermal model to analyze the data, which were acquired through calorimetry analysis. The simulation was accomplished for a complete discharge cycle. The ANSYS model employed a combination of heat transfer experiments and simulations, including computational fluid dynamics and the results of the experiments in the isothermal battery calorimeter. [34**].**

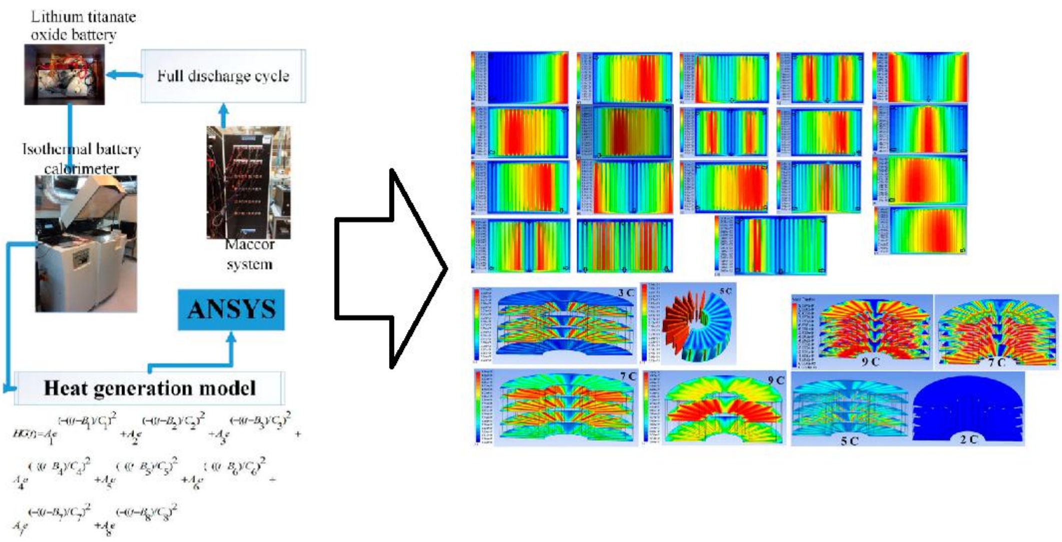

Figure 3. The integration of the ANSYS with the heat generation model and modelling results [33,34].

3. Thermal Effects and thermal modelling of lithium-ion batteries

The detailed and comprehensive impacts of temperature on lithium-ion batteries' heat loss are indispensable to be identified. A three-dimensional heat conduction equation requires to be solved with the intention of gaining the temperature distribution in a cell which can be described as [35]:

$$\rho C \frac{\partial T}{\partial \tau} = \nabla . (k \nabla T) + Q$$

ρ: Density C: Specific heat capacity K: Thermal conductivities Q : Volumetric heat source

Shovon Goutam et al. [36] selected a systematic pattern to study the effect of current rates on the thermal behaviour of LIB. In this way, it was possible to analyze and observe the temperature evolution and variations between narrower intervals of current rates. Various parameters were determined, including the lithium-ion battery current, voltage, surface temperature, heat flux, and maximum temperature. Using the determined models, it was possible to determine the heat loss for all charge and discharge cycles, with a different current. In addition, it is possible to comprehend the increasing and decreasing trend of temperature. This research studied the development of temperature distribution, thermal behaviour, and cell thermal performance. Furthermore, the heat generation model was computed at various temperatures and different charging and discharging scenarios. More than that, the highest jump in the lithium-ion battery temperature was measured. A wide range of charge and discharge current rates were selected to determine the battery's heat generation and surface temperature evolution.

The thermal image of the battery during charging and discharging is illustrated in Figure 4. More energy is transferred to less electrical resistance areas than areas with more significant electric resistance attributable to the lower current density in areas with more significant resistance. Consequently, temperature gradients appear on the surface of lithium-ion batteries. The displacement of the hot spot location may be attributable to the electrical cell design. Besides, it could be seen for smaller environment temperatures. The growing variation between lithium-ion battery cell temperature and the environment causes a relocation of the hot spot approaching the lithium-ion battery cell's tab due to the heat transmission's rising influence because of the load wires on the tabs.

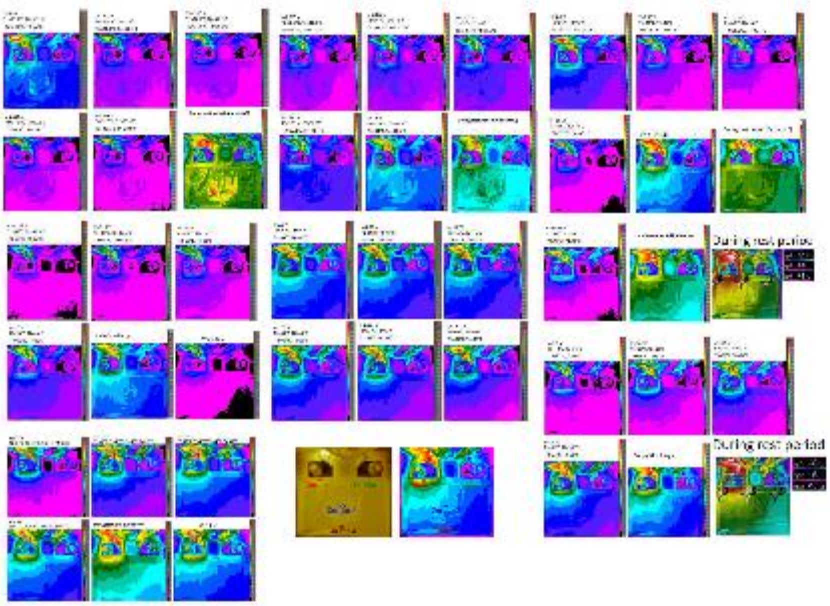

Figure 4. Thermal image of the battery during charging and discharging [37].

Operating temperatures of LIB play essential roles in power storage systems. Investigations with a focus on the thermal properties of LIB have been accomplished previously. One of the important drivers for these studies was decreasing the risk of thermal runaway and improving LIB thermal stability, which are affected by the electrode's characteristics, including the applied materials [38]. Several researchers have investigated the influence of thermal behaviour on LIB performance. Using different Experimental and simulation approaches. S.C. Chen et al. [39] developed a comprehensive three-dimensional thermal model to investigate the thermal behaviour of a lithium-ion battery. The thermal model's simulation outcomes exhibited asymmetrical temperature distribution. Hall et al. [40] demonstrated that lithium titanate as an anode material provided exceptional stability. The capacity, however, turned out to be strongly temperature-dependent.

Yasir Abdul-Quadir et al. [41] employed a large-capacity lithium-ion battery cell to determine heat generation. The generated heat was quantified by entropic heat and over-potential heat. In addition, over-potential heat was quantified by measuring dissimilar resistances. It was demonstrated that the entropy coefficient transformed from exothermic to endothermic, which was mainly attributable to structural rearrangements at the anode. Another study investigated the impact of a lithium-ion battery's design parameters on heat generation. It was demonstrated that the design parameters and working conditions significantly influence the kinetics. The outcomes exhibited that LIB with a thin layer thickness had a minor temperature increase [42].

In the field of thermal modeling of batteries, various methods have been used, including integral methods, enthalpy, and special heat capacity, which are shown in Figure 5. Extensive studies on discretization methods have also been performed on the mentioned methods.

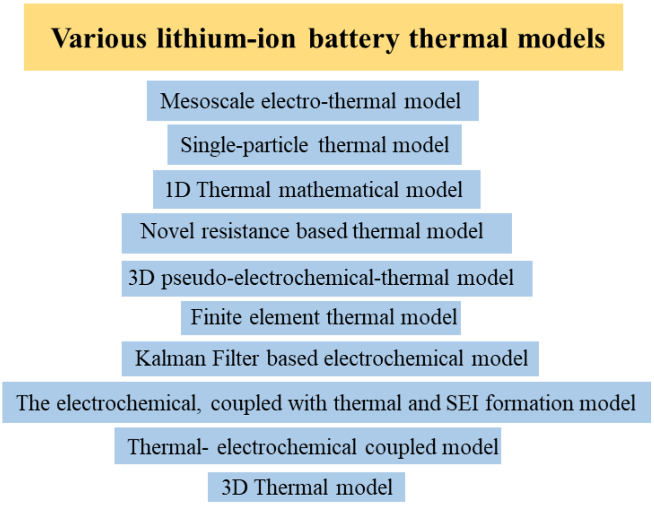

Figure 5. Different methods for thermal modelling of lithium-ion batteries [43].

4. Thermal management systems for lithium-ion batteries

The in-depth understanding of the thermal effects in LIB, which is enabled by the findings of the described experiments using calorimetric methods and the thermal modelling approaches allows to development of a well-adapted thermal management system. This ensures that the cell is kept as much as possible under the optimum operating conditions. Various fluids such as air and water can be used in the field of active cooling in batteries. In addition, passive methods including heat pipes and phase change material approaches have been proposed. A simple battery thermal management system that can be used for comparing air and liquid cooling systems is illustrated in Figure 6. In recent years, various studies have been conducted on designing different thermal management systems for LIB. Various innovative liquid coolant-based thermal management approaches for a pack were proposed by different researchers. Among these methods, we can mention different methods such as heat pipe-phase change material, air-heat pipes, air-phase change material, and air-phase change material-heat pipe.

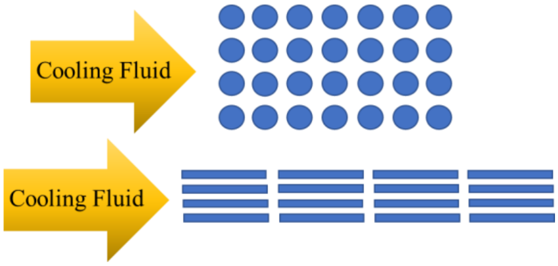

Figure 6. Simple battery thermal management system.

A comparison between the different methods for thermal management of lithium-ion batteries through the evolution of heat loss and studying their thermal and electrochemical behaviour was systematically elaborated. Several simulations were carried out to calculate the lithium-ion battery's cooling by altering the stream velocity and coolant direction in liquid cooling, fin cooling, and air cooling. studies demonstrate the temperature distributions over the lithium-ion battery's surface at different velocities and flow directions for air-cooling and direct liquid cooling and the temperature profile for liquid cooling and fin cooling. Air-cooling's temperature profile was approximately identical to direct liquid cooling, nevertheless, it has a more significant temperature impact on the battery cell. Studies displayed the temperature profile for indirect liquid cooling, jacket, and coolant. As expected, the hottest zone position was seen adjacent to the cooling liquid's exit, and the position of the coldest zone was seen adjacent to the entry of the cooling liquid. The non-uniform heat distribution was found. The cycling termination displays smaller temperatures adjacent to the cooling liquid's entry and more significant temperatures at the cooling liquid's exit. The amount of heat generation was proportional to the cooling flow velocity. The temperature of the LIB was manageable with an immense velocity of coolant fluid. Notwithstanding, with an increase of cooling flow velocity to a value larger than a specific value for air cooling, direct liquid cooling, and direct liquid cooling, correspondingly, a considerable cooling of the LIB was not obtained [44].

Mahesh Suresh Patil et al. [45] studied numerically different factors influencing liquid cooling cold plates for a lithium-ion pouch cell. It was seen that the cooling effect of the cold plate is influenced by multiple factors, including the number of channels and the inlet mass flow rate of the coolant. By enlarging flow velocity, the heat transfer coefficient raises, the most significant temperature increases declines, and temperature non-homogeneity is decreased at the expense of rising pressure reduction and energy utilization; consequently, the operational costs raise. Although the fluid heat capacity is a significant coefficient, the costs related to pressure drop and power or fan or pump power to drive the fluid and less complexity in design and low cost and weight should be considered. Different coolant arrangements were selected, and the results were compared to demonstrate the effect of different flow distributions in the coolant channel. In addition, the impacts of essential design parameters on the cold plate's thermal performance were numerically studied. It was concluded that channel width, number of channels, the inlet mass flow rate, and inlet temperatures have a significant influence on cold plate temperature. They studied the thermal performance of a water-cooled lithium-ion pouch cell at a big discharge rate using a microchannel cold plate.

In another work, Mahesh Suresh Patil et al. [46] numerically studied cooling plates accompanied by dissimilar constructions for electric vehicle thermal management systems. The impact of channel distribution and cooling direction on the cooling structure's thermal behaviour and performance for the LIB was investigated. The LIB was sandwiched between two cold plates. The liquid water was assumed to flow into the entrance channels with coolant temperature and a different mass flow rate. The pressure distribution for different cases was described. The produced heat was transferred into the cold plate and relocated by the coolant fluid afterwards. Different designs were considered for the direction of flow in the cooling plate. The pressure decline demonstrates the pump energy to overcome the flow resistance of the coolant fluid. The most significant temperature of the cooling plate could demonstrate the most severe working condition of lithium-ion batteries. Compared to other cases, the cold plate's highest temperature uniformity happens when the number of conduits was higher, and the inlet temperature was lower. It was concluded that the design with ten conduits was the best.

A cold plate is an extensively used design for LIB. Different lithium-ion battery shapes and models were investigated for different flow distributions in the coolant channel and different conventional coolant fluids. The scope of working flow velocity for every cooling approach was accurately and thoroughly investigated to manage the temperature increase under different working conditions. Moreover, the fluid pressure drop in the collection and flow distribution were calculated for each item. [47-50]. An overview of such thermal management system approaches using cold plates is given in Table 1.

A multipurpose cooling plate was designed and investigated for the thermal management of prismatic lithium-ion batteries throughout thermal runaway and normal working. The coolant's pressure decline was approximately 75 Pa for the usual working mode and approximately 54 kPa for the cooling plate's thermal runaway working condition [51]. S. Panchal et al. [52] studied the simulation and thermal design of the mini-channel cold plate for a prismatic lithium-ion battery. A significant airflow rate requires being distributed inside the chamber to attain efficient temperature management for dissipating the generated heat in the lithium-ion battery. The aforementioned is not commonly accomplished attributable to the chamber's incapability to enhance the flow rate. It was seen that operating temperature and discharge rate has the most significant influence on the temperature of the cold plate.

The lithium-ion battery module accompanied by a water-cooling plate and phase change material was structured and numerically investigated according to the fluid dynamics and energy conservation to improve the operational efficiency of a LiFePO4/C LIB. In addition, the non-uniform inner heat source, according to the 2D electrothermal model for the LIB, was employed to simulate heat loss [53].

Jianguo Wang et al. [54] studied the thermal behaviour enhancement of a LIB pack with various cooling structures. The outcomes displayed that an arrangement that employs a short length-width proportion is more advantageous to elevating the cooling arrangement's performance. The entrance and exit arrangement of the cooling configuration, which eases fluid stream through most of the pack over reduced lengths, is more advantageous to thermal management. The arrangement of a significant quantity of entrances and exits could ease a more flexible arrangement of the fluid stream condition and decrease LIB heating. Thermal management of a prismatic lithium-ion battery was investigated by using a mini-channel cold plate. It was concluded that larger flow rates are required at higher discharge rates to attain cooling performance [55].

Experimental facilities were established to determine the temperature impact on lithium-ion battery performance and design different thermal management methods. The quantification of heat generation for LIB at different charge and discharge rates and working conditions was investigated. According to these performance outcomes, the thermal model, which was capable of predicting the lithium-ion batteries' thermal behaviour, was improved and experimentally validated. It was concluded that heat accumulation and heat generation are not uniform over the lithium-ion battery's surface. Remarkably, the thermocouples seated near the tabs sensed temperature, which was more significant than at other positions. It was observed that the experimental results are in good agreement with the data from the model. Considerable temperature heterogeneity was observed at the lithium-ion battery cell surfaces because of the more effective current rate. Correspondingly, a suitable thermal management system was designed. The thermal management system could play an essential role in stopping the lithium-ion battery cell's immense temperature growth during significant current rates of discharging and charging. With the increase in the charge and discharge current rates, the temperature distribution became less spatially homogeneous over the lithium-ion battery's entire surface. The most significant area is positioned near the tab's division of the lithium-ion battery. This finding might be inferred from the quicker discharge of the active species adjacent to the tab area owing to the more significant current density [56-58].

A new method for lithium-ion battery thermal management was designed by Y. Yuang et al. [59] using mini-channel cooling plates with streamlined configurations. They found that the most significant improvement of the heat exchanger performance accompanied by streamlined configuration design could be as large as about 44% [59]. Madani et al. [60] studied the thermal behaviour of cold plates for cooling lithium-ion batteries through thermal characterization. The cold plate was supposed to be isotropic and homogenous for numerical simplicity. The influence of inlet temperature and the number of channels on the cold plate's thermal behaviour was described. It can be seen that the most significant decrease in maximum temperature happens when the number of channels is ten and the inlet temperature was the lowest.

Four different multichannel cooling plates accompanied by honeycomb assembly, including convex assembly, airfoil assembly, and U-shaped assembly, were constructed as specified by the particular heating state of a rectangular lithium-ion battery pack [61]. T. Amalesh et al. [62] studied the influence of different cases on the cold plate's thermal behaviour. The construction of the cooling plate was considered comparatively complex. Furthermore, the channel configuration of the cold plate was considered comparatively simple. Water was considered as cooling mass media in the lithium-ion battery cooling for various typical current distributions and arrangements. It was concluded that zig-zag and circular slots channels showed good cooling performance.

Table 1. The thermal management system of lithium-ion batteries using cold plates.

Investigation	Conclusion	Ref
-Influencing factors of double cold-plate: Numerical study	The inlet temperature of coolant has the greatest influence on the battery (contribution:99.31%)	Patil et al.

- Sensitivity analysis		[45]
Cooling performance characteristics	The greatest pressure descend of the coolant is 227.6 Pa for 4-channels and the mass flow rate of 0.001667 kg/s	Patil et al. [46]
Study of a cooling system	The cell's temperature differences and temperature could be held within an ideal scope.	Chu et al. [47]
-Heat dissipation analysis - Flat heat pipe	The highest temperature variation of the average temperature for batteries moderately raise and arrive at the highest at 3 C	Mei et al. [48]
-Thermal analysis - Multi-domain modelling framework	The generated heat by the cells collects within the module, which creates a big risk of thermal runaway for a big-scale battery pack	Zhang et al. [49]
Optimization and analysis process	The temperature decrease was greater,1.87 °C; and the temperature deviation could be controlled within a negligible range, 0.35 °C	Chen et al. [50]
-Dual-purpose cooling plate - Normal operation and thermal runaway conditions	-The system could retain the battery temperature under 25 °C during normal operation. - The pressure drop of coolant was 75 Pa	Haq et al. [51]
Thermal design and simulation	-Elevated working temperature and discharge rates leads to the elevated temperature of the cold plates	Panchal et al. [52]
Effect study on thermal behaviour enhancement	The optimal combining could decrease the greatest temperature variation to 3.52 K and control the highest temperature under 302 K	Wang et al. [54]
Thermal Management by mini-channel cold plate	Discharge rate: 2 C Flow rate: 0.002 kg s−1 Inlet coolant temperature: 30°C Maximum temperature: 33.8°C Temperature difference: 3.5°C	Shen et al. [55]
A new method for lithium-ion battery thermal management	The utmost improvement of the heat exchanger efficiency can be as big as 44.52% by using a stream-line shape design	Huang et al. [59]
-Numerical analysis with different structures for electric vehicle	-The convex design has a better cooling performance -The heat transfer performance of dissimilar systems alters a large amount with the enhancement of mass flow rate	Li et al. [61]
- Novel designs of mini-channel	- The zig-zag and circular slot channels provided the advantageous cooling performance - Improved temperature homogeneity achieved with the whole of the designs	Amalesh et al. [62]
Thermal performance of a heat pipe system	Ambient temperature < 35 °C: the thermal performance of the system could be held approximately constant by decreasing the coolant temperature.	Liang et al. [63]

Phase change materials can play a unique role in battery temperature management. Different requirements of phase change materials are illustrated in Figure 7. The presence of these materials in the vicinity of lithium-ion batteries can keep the temperature of the batteries at a low level and provide a uniform temperature in the whole battery pack [64,65]. One of the unique features of phase change material is that it can store a large amount of heat energy and transfer it to the outside in other circumstances [66]. Also, these materials can absorb the heat from the damaged battery in case of a thermal runaway due to their high ability to absorb and store heat and prevent from spreading of this phenomenon [65,67]. An overview of such thermal management system approaches using phase change materials is given in Table 1.According to a recent study, the main goal of a large amount of research is focused on the use of different phase change materials in order to increase the heat transfer coefficient of these phase change materials, which has been shown to be extremely effective. Increasing the heat transfer coefficient in these phase change materials has been done with the aim of reducing the maximum temperature of the batteries and distributing the appropriate temperature in the battery pack. [68-74]. It can be concluded from the study that the methods in which phase change materials are used significantly help to lower the battery temperature [75].

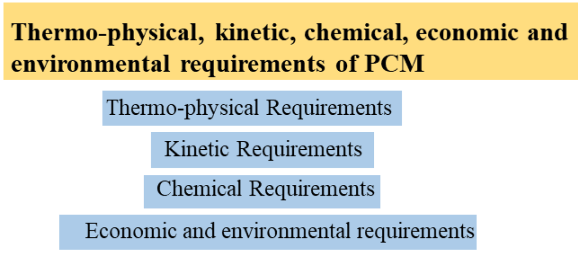

Figure 7. Different requirements of phase change materials [76].

Table 2. The thermal management system of lithium-ion batteries using phase change materials.

Investigation	Material	Conclusion	Ref
Thermal performance of a composite board: Numerical study	Composite board	Enlarging the latent heat of phase change material could considerably enhance the thermal performance of the composite board.	Yan et al. [65]
Preventing thermal runaway propagation: an experimental study	Phase change composite	The cooling materials decrease the greatest temperature of cells	Wilke et al. [67]
A multiscale study for thermal management	Graphene or h-BN paraffin composite structures	Graphite network composites produce the dominant performance in thermal management	Mortazavi et al. [68]
A thermal management system: Experimental and numerical investigation	Cutting copper fiber sintered skeleton/paraffin composite	The heating rate of the battery pack lessens with enhancement in the quantity of pores per linear inch	Pan et al. [69]
A novel method for battery thermal management	nanosilica-enhanced with anti-leakage and anti-volume-changes properties	these enhanced properties of cooling material present better cooling durability and efficiency	Lv et al. [71]
Thermal management performance of phase change materials at low temperatures	60 wt% RT44HC/expanded graphite (EG) composite + 60 wt% RT44HC/fumed silica composite	The small thermal conductivity of the material results in bigger temperature variation over the battery pack	Ling et al. [72]
Phase change materials for thermal management of batteries	Graphene-enhanced hybrid	Graphene incorporation causes a considerable decline in the temperature increase in Li-ion batteries	Goli et al. [73]
A passive thermal management system for high-powered batteries	Nickel foam-paraffin composite	The utilization of cooling material could substantially decrease the surface temperature inside the permissible range	Hussain et al. [74]
Thermo-mechanical behaviours for thermal management of battery packs	Expanded graphite-phase change material matrix	When the mass fraction of paraffin wax enhances in the composite material, the thermal conductivity was bettered	Alrashdan et al. [75]
Effective heating approaches for power battery	Phase change material	The performance of the forced-air convection, heating approaches could be increased by assembling a close-ended battery pack	Lv et al. [77]

5. Conclusion

Lithium-ion batteries are one of the most important options for storing electrical energy. Today, with the development of electric cars, hybrids, phones and tablets, the use of batteries with high storage volume is required. Therefore, modelling batteries and examining their temperature distribution and heat transfer for a wide range of charge and discharge current rates, including low and fast charging is very important. Thus, the study of battery heat transfer helps designers to propose and develop a suitable cooling system. Efficiency is a non-dimensionalized parameter produced by electrical power and heat generation. The efficiency presents a more straightforward illustration of the heat generation characteristics all over the experiments. This non-dimensionalized parameter is under one for all charge and discharge rates. Notwithstanding, the efficiency of heat generation has a different quantity for different charge and discharge rates. Generally, information about lithium-ion batteries, including physical composition and properties, is unavailable. The aforementioned makes the thermal model and management of lithium-ion batteries an extraordinarily challenging task for researchers. Notwithstanding, there is insufficient comprehension regarding the practical technique to thermally control the lithium-ion battery cells in a pack. Previous studies did comprehensively investigate lithium-ion batteries' thermal behaviour and management during different charge/discharge cycles which demonstrates a considerable scientific advancement and improvement in the comprehension of thermal behaviour and management of LIB using different methods and exceptional experimental setup. In addition, different coupled three-dimensional electrochemical and thermal models were built by different researchers for lithium-ion batteries and packs. The models were employed to assess various working states' impacts, including discharge current and coolant flow rate on the pack temperature. It was concluded that thermal contact resistance significantly influenced the lithium-ion battery pack's thermal performance. Lithium-ion batteries are continuously charged and discharged for different applications, including electric vehicles. Accordingly, air or liquid cooling must remove the system's heat. Interspacing should be considered to provide sufficient air or liquid cooling circulation to remove heat. It can be concluded that the cooling effect can be significantly increased by combining both active and passive methods. The in-depth understanding of the thermal effects in LIB, which is enabled by the findings of the described experiments using calorimetric methods and the thermal modelling approaches finally allows to development of a well-adapted thermal management system.

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