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Review article

Recent advancements in battery thermal management system (BTMS): A review of performance enhancement techniques with an emphasis on nano-enhanced phase change materials

Ghulam Rasool [a], Wang Xinhua [a,*], Tao Sun [a,**], Tasawar Hayat [b], Mikhail Sheremet [c], Azim Uddin [d], Hasan Shahzad [e], Kamil Abbas [a], Izzat Razzaq [a], Wang Yuexin [a]

[a] *College of Mechanical and Energy Engineering, Beijing University of Technology, Beijing, 100124, China*
[b] *Department of Mathematics, Quaid-i-Azam University, Islamabad, 44000, Pakistan*
[c] *Laboratory on Convective Heat and Mass Transfer, Tomsk State University, 36 Lenin Avenue, Tomsk, 634050, Tomsk, Russia*
[d] *Zhejiang(Shaoxing) High-Level Foreign Experts Innovation Center, Chuangyi Road, Keqiao District, Shaoxing, 312030, China*
[e] *Faculty of Energy and Power Engineering, School of Chemical Engineering and Energy Technology, Dongguan University of Technology, China*

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ABSTRACT

Because of their numerous benefits such as high charge cycle count, low self-discharge rate, low maintenance requirements, and tiny footprint, Li-batteries have been extensively employed in recent times. However, mostly Li-batteries have a limited lifespan of up to three years after production, may catch fire if the separator is damaged, and cannot be recharged when they are fully depleted. Due to the significant heat generation that li-batteries produce while they are operating, the temperature difference inside the battery module rises. This reduces the operating safety of battery and limits its life. Therefore, maintaining safe battery temperatures requires efficient thermal management using both active and passive. Thermal optimization may be achieved battery thermal management system (BTMS) that employs phase change materials (PCMs). However, PCM's shortcomings in secondary heat dissipation and restricted thermal conductivity still require development in the design, structure, and materials used in BTMS. We summarize new methods to control temperature of batteries using Nano-Enhanced Phase Change Materials (NEPCMs), air cooling, metallic fin intensification, and enhanced composite materials using nanoparticles which work well to boost their performance. To the scientific community, the idea of nano-enhancing PCMs is new and very appealing. Hybrid and ternary battery modules are already receiving attention for the li-battery life span enhancement ultimately facilitating their broader adoption across various applications, from portable electronics to electric vehicles and beyond.

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[*] Corresponding author.

[**] Corresponding author.

E-mail addresses: grasool@bjut.edu.cn (G. Rasool), sunxhking@aliyun.com (W. Xinhua), tsun@bjut.edu.cn (T. Sun), fmgpak@gmail.com (T. Hayat), sheremet@math.tsu.ru (M. Sheremet), auddin@zju.edu.cn (A. Uddin), hasanshahzad@dgut.edu.cn (H. Shahzad), kamil_abbas3@hotmail.com (K. Abbas), izzatrazzaq@yahoo.com (I. Razzaq), w1104141754@163.com (W. Yuexin).

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1. Research background

As widely used in energy storage and transmission, Li-batteries are one of the major sources of covering the requirement of power consumption across the globe. However, it is limited by the poor thermal performance and weak thermal management system that directly impact the battery life. This occurs due to the engagement of poorly conductive materials and pure PCM coatings. On the other hand, the malfunctioning, heating up frequently, and poor performance of battery thermal management system (BTMS), are difficult to eradicate especially with an increase of electric passage and current capacity, charging and discharging at a higher temperature environment, and its pulsation peak, resulting in the drastic heat up of battery. In addition, with the increase in charging speed, the heat flux phenomena in the BTMS undergo a drastic change that results in more energy loss due to low thermal performance of PCMs and other materials. To boost the performance, life-span and working capacity of Li-batteries, an improved battery thermal management environment, and enhanced capacity of phase change materials combined with air-cooling and nano-enhancement procedures certainly work fine, which may lead to a great improvement in the industry [1–5]. There is a long process involved in designing battery thermal management systems. The major steps are listed below.

(1) The BTMS design objectives and constraints must include dimensions, shape, orientation, quantity, heat transfer medium, maximum pressure drops, ventilation needs, and budget.
(2) Examining how quickly heat is generated in each battery cell and where in the pack temperatures vary for various loads. This information may be gleaned from thermodynamic, thermal enhancements, and electrochemical models of the batteries.
(3) Measurement, analysis, or approximation of the behavior of materials at varying charge levels and temperatures may reveal thermophysical features such as the heat capabilities of constituent components (cell core or casing) of batteries. Calorimeter methods and mass-weighted medians of cell/module components may be used for this purpose.
(4) The contact temperature between the module and thermal management system is determined under varying loads.
(5) Energy efficiency and heat transfer are often used to accomplish this. To be comprehensive, this kind of study must take into consideration a variety of flow routes and velocities, in addition to key heat transfer mediums (air, liquid).
(6) Determining heat transfer fluid’s thermal conductivity for the BTMS. CFD, correlations, and experimental methods are often used at this level.
(7) The projected performance of the BTMS is evaluated based on thermal attributes of battery system and the estimated cooling load for the said system.
(8) BTMS mostly comprises fans, pumps, evaporators, and heaters, among other ancillary components. Energy consumption, system complexity, performance, and maintenance are all important design characteristics that may be established and compared to other options. When necessary, designers incorporate practical constraints that aren’t taken into consideration in simulation and redo earlier design phases with the new knowledge to best meet the design criteria.

In all designs of BTMS, the understanding of thermal performance of battery systems is essential. Fig. 1 is a simplified illustration of a battery system’s thermal behavior. The total heat output in a battery is from many different processes, including the intercalation and deintercalation of the existing ions (i.e., entropic heating), the heat of phase transition, overpotentials, and the heat discharge due to mixing. While the previous three are instances of irreversible heating phenomena. Entropic heat is an example of reversible heating since it reflects the heat created during the reversible isothermal maneuver of a battery [6]. Electrochemical reactions (heat production during charge transference between electrode and electrolyte in electrode reactions), electron flow (heating due to Joule effect or ohmic resistance), and ionic movement in the electrolyte are the three primary sources of heat generated by overpotentials.

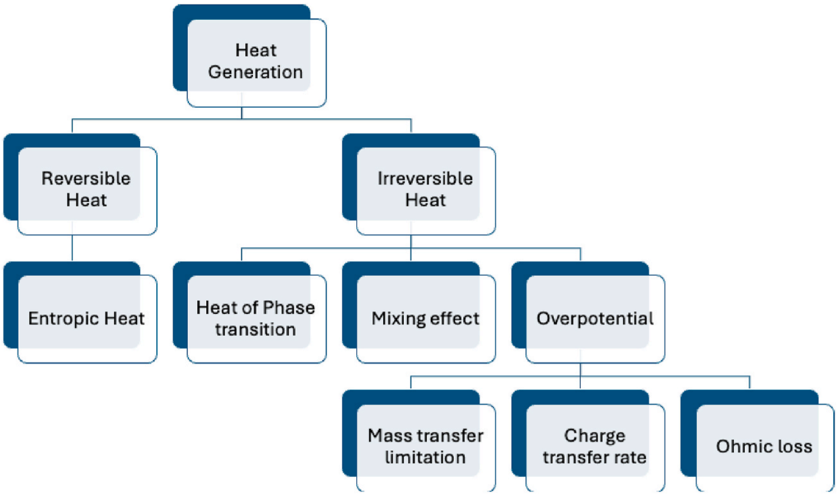


Fig. 1. Thermal behavior of battery system and heat flow chart.

Battery Thermal Management Systems (BTMS) are crucial for maintaining the optimal temperature range of batteries, particularly in high-performance applications like electric vehicles (EVs) and portable electronics. These systems can be broadly categorized into active and passive BTMS. Here's a detailed differentiation between the two.

1.1. Active battery thermal management systems (BTMS)

Active BTMS utilize external energy sources and mechanical or electrical components to actively control the temperature of the battery pack. It comprises fans, pumps, compressors, or thermoelectric coolers, involving the circulation of coolants (liquid or air) through the battery pack to monitor temperatures and adjust the cooling/heating mechanisms accordingly.

1.1.1. Working principle

1. Active systems might use liquid cooling, where a coolant is pumped through channels adjacent to the battery cells, absorbing heat and carrying it away to a radiator or heat exchanger. Air cooling might involve fans blowing air over the battery pack.
2. In cold conditions, active systems can heat the batteries using electric heaters or by reversing the thermoelectric cooler operation.

1.1.2. Advantages

1. Active BTMS can maintain a precise temperature range, enhancing battery performance and lifespan.
2. It can quickly respond to changes in temperature due to active monitoring and control mechanisms.
3. It is suitable for large-scale applications, like EVs, where precise thermal management is crucial.

1.1.3. Disadvantages

1. It requires additional energy to operate cooling/heating devices, potentially reducing overall system efficiency.
2. More complex system architecture and higher initial and maintenance costs due to additional components and control systems.

1.2. Passive battery thermal management systems (BTMS)

Passive BTMS relies on natural heat dissipation and material properties to manage battery temperatures without the use of external energy sources or mechanical components such as phase change materials (PCMs), heat pipes, and thermal interface materials. In addition, it may include metal components designed to absorb and dissipate heat allowing air to flow naturally over the battery pack.

1.2.1. Working principle

1. Using materials with high thermal conductivity to transfer heat away from the battery cells to heat sinks or other dissipative surfaces.
2. These materials absorb and release thermal energy during phase transitions (e.g., from solid to liquid), helping to stabilize temperatures.
3. Leveraging airflow around the battery pack without mechanical assistance.

1.2.2. Advantages

1. Does not require additional power for operation, making it energy-efficient.
2. Fewer components reduce the risk of mechanical failure and lower maintenance requirements.
3. Generally lower initial costs and maintenance expenses due to simpler designs.

1.2.3. Disadvantages

1. Less precise temperature management compared to active systems, potentially leading to less optimal performance under extreme conditions.
2. Slower response to rapid changes in temperature, which might not be suitable for high-performance applications.
3. May not be as effective for large-scale applications requiring precise thermal control.

High voltage and increasing temperature will deteriorate the output performance of the existing battery thermal management system, and thus risk for loss of energy, damage to battery life, and low storage capacity is always there. The poor working materials in the insulation of BTMS, and the poor insulating surface are the core reasons for more frictional or drag force, or loss of energy due to less conductive properties of the material used in BTMS and the poor thermal conductivity of the PCMs, therefore, energy loss increases, resulting in the decline of efficiency, life-span and working capacity of the battery, ultimately battery life reduces. The development of high-voltage storage requires the complete alteration in the structural principle of BTMS and the creation of new structures that can overcome these barriers [7]. The inherent defects of BTMS truly meet the technical need of thermal management systems to be improved to overcome the structural limitations and poor performance of the battery. Each energy storage device configuration has its own structural and operational characteristics; even the same type of device can have different configurations to suit completely different applications and working conditions, such as efficient thermal management arrangements in Li-batteries to avoid overheating. The innovative BTMS designs may cut PCM melting and charging times while also maintaining the battery's thermal state and efficiency when the surrounding temperature rises above 40° [6,8].

2. Literature review

Integrated battery thermal management systems (BTMSs) built using phase change material (PCM) are commonly used in various industries. However, cylindrical battery modules' curved surfaces and the PCM module's small and huge cuboid design make integrated BTMSs a formidable obstacle. Therefore, researchers focus on tackling these issues. For instance, Mo et al. [9] incorporated force air convection and a unit-assembled composite PCM (CPCM) module in BTMS. The CPCM module, which is put together using CPCM modules that resemble sleeves, improves convective heat transmission by creating expanded airflow channels and increasing the heat transfer surface. So, in cooling and preheat modes, the heat flow is increased, and the thermal resistance of the units-assembled module is significantly lowered when compared to the standard cuboid-shaped module. The BTMS does very well in cooling tests, keeping the temperature below 40.30 °C and the temperature differential below 2.80 °C at a 3-C discharge, respectively. While conducting preheating tests, it successfully brings the temperature of the battery module up to 10 °C in only 302 s, with a relatively small temperature differential of 3.82 °C. Yao et al. [10] studied the leakage owing to poor capillary condensation from its micron-scaled polymer framework with mainstream phase change materials (PCM) used for thermal control of battery modules. A leakage-proof and highly stable composite PCM (CPCM) was proposed in this study by using a one-pot technique to in-situ manufacture a nano-scaled resorcinol-furfural polymer framework (RF-PF) in PCM. The nano-scaled RF-PF stacks into a three-dimensional meshoporous structure, providing a much higher level of adsorbability towards PCM and preventing leakage, in contrast to the traditional micron-scaled epoxy resin framework. The RF-CPCM exhibits stable and effective thermal management capabilities towards pouch and cylindrical battery modules when coupled with appropriate thermo-physical properties, a phase change temperature region of 40–55 °C, and a thermal conductivity of 1.58 $Wm^{-1}K^{-1}$. The RF-CPCM module successfully eliminates the leakage trace that appears on the conventional CPCM module during the accelerated aging test. Ye et al. [11] investigated the battery thermal management technology based on phase-changeable polymer (PCP) framework in-situ in a polyethylene glycol (PEG)/expanded graphite (EG) slurry to create a new composite phase change material (CPCM) with two PCTRs. The latent heat of the lower PCTR at 31.7–42.1 °C from the PCP framework is 35.0 Jg^{-1}, as produced, while the latent heat of the higher PCTR at 42.1–51.2 °C from the PEG is 68.3 Jg^{-1}. Consequently, with a 1C discharge rate and an ambient temperature of 25 °C, the battery module is able to operate efficiently within the 25.9–34.9 °C temperature range thanks to the decreased PCTR and a low temperature differential (ΔT) of 2.4 °C.

2.1. *Li-batteries*

2.1.1. *Working principle*

Electrochemical reduction and oxidation (redox) processes allow primary Lithium-ion batteries to gain electrical energy from the

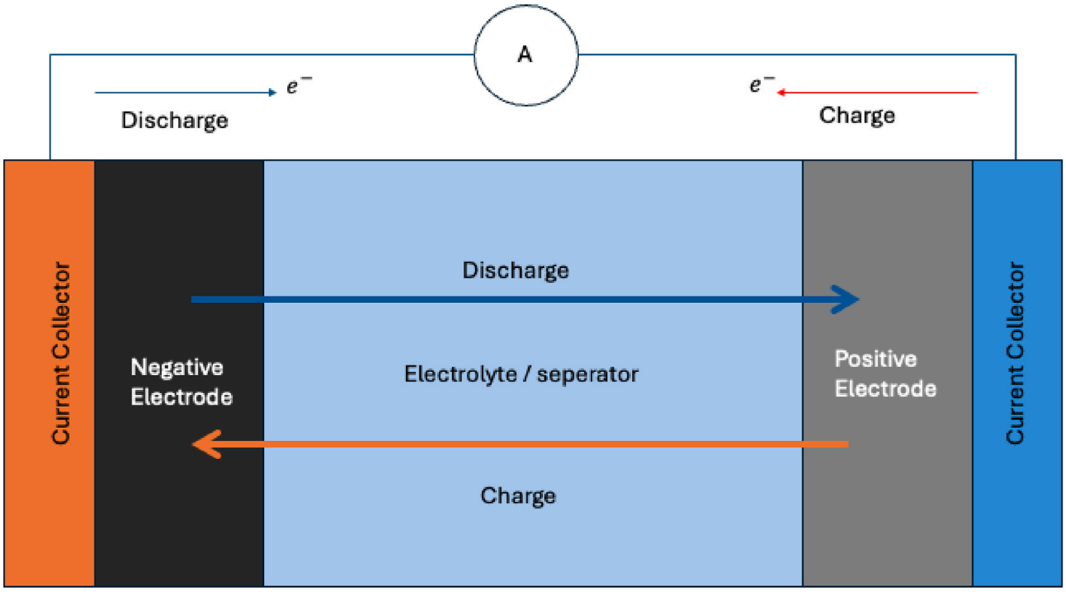


Fig. 2. Basic configuration of a Li-battery.

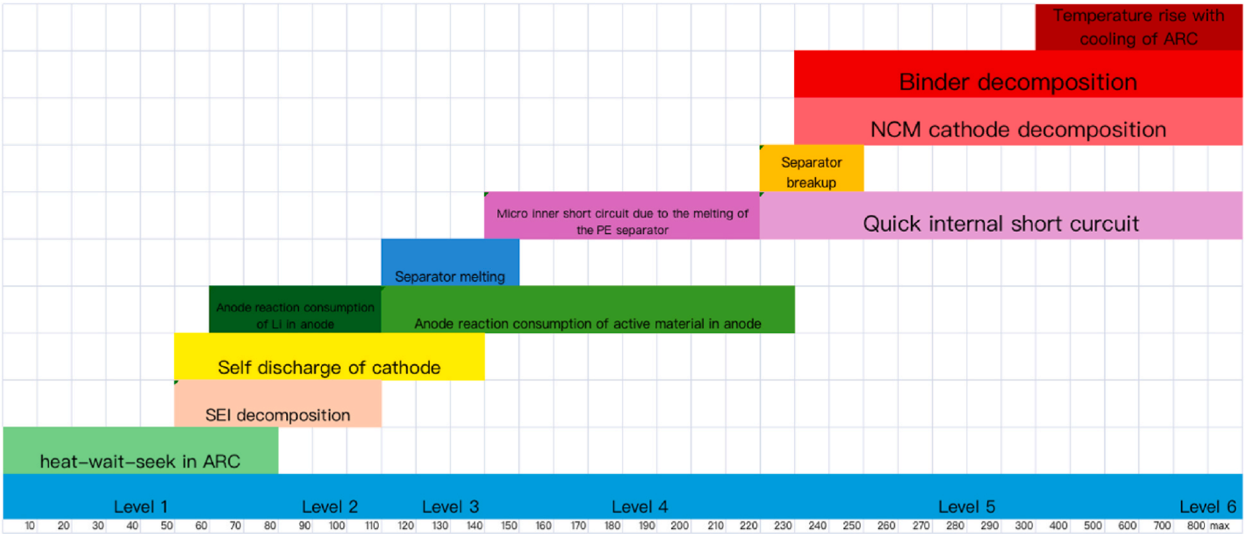


Fig. 3. EV-ARC thermal runaway testing temperature ranges for several phases.

transition of chemical energy. These processes may be reversed in Li-batteries, making them secondary batteries capable of converting chemical energy back into electrical energy. That's how secondary batteries diverge from their main counterparts, whose chemical energy is permanently transformed into electricity [12].

2.1.2. Components

Fig. 2 provides a simplified diagrammatic representation of a Li-ion battery. Here, five primary elements are represented by distinct hues. The current collectors, which are covered with the active electrode materials, are shown at both ends. The positive and negative current collectors in commercial Li-ion batteries typically consist of aluminum and copper, respectively. Electrons are transferred from

Table 1
Comparative analysis of Life-Span of Li-batteries and others.

	Lithium-Ion (Li-ion)/Li-Batteries	Lead-Acid Batteries	Nickel-Cadmium (Ni-Cd) Batteries	Nickel-Metal Hydride (NiMH) Batteries	Solid-State Batteries
Cycle life	Li-batteries typically offer a cycle life of 300–1000 cycles, depending on the specific chemistry (such as NCA, NMC, LFP) and usage conditions. High-quality Li-batteries can even exceed 1000 cycles with proper management.	Lead-acid batteries, including both flooded and sealed types, have a shorter cycle life compared to Li-batteries. They typically range from 200 to 800 cycles, with deep-cycle variants on the higher end.	Ni-Cd batteries have a cycle life of about 1000–1500 cycles, making them relatively robust compared to lead-acid batteries but still generally lower than high-quality Li-batteries.	NiMH batteries offer a cycle life of approximately 500–1000 cycles, which is better than lead-acid but can be less than Li-ion under certain conditions.	Solid-state batteries, still in the developmental and early commercialization stages, promise very high cycle lives, potentially exceeding 1000 cycles, like or better than Li-ion batteries.
Calendar life	The calendar life of Li-batteries is generally 5–10 years. Advances in battery management systems (BMS) and improvements in battery chemistry continue to extend this lifespan.	The calendar life of lead-acid batteries is around 3–5 years, though this can be lower under heavy cycling or poor maintenance conditions.	The calendar life of Ni-Cd batteries can extend up to 10 years under ideal conditions.	NiMH batteries typically have a calendar life of 5–7 years.	The calendar life of solid-state batteries is projected to be superior, possibly exceeding 10 years, due to their solid electrolyte, which reduces issues related to liquid electrolyte degradation.
Performance degradation	Li-ion batteries experience gradual capacity loss over time due to factors like high temperature, deep discharges, and high charging rates. Typically, a well-maintained Li-ion battery retains about 80 % of its original capacity after 3–5 years of regular use.	Lead-acid batteries suffer significant degradation if frequently discharged beyond 50 % of their capacity, and they are highly susceptible to sulfation, which reduces their capacity over time.	Ni-Cd batteries are prone to the "memory effect," where partial discharge cycles can lead to a reduced effective capacity. However, they are more tolerant of high discharge rates and extreme temperatures.	NiMH batteries do not suffer from the memory effect as severely as Ni-Cd batteries but can experience significant self-discharge rates and capacity degradation over time.	The calendar life of solid-state batteries is projected to be superior, possibly exceeding 10 years, due to their solid electrolyte, which reduces issues related to liquid electrolyte degradation.

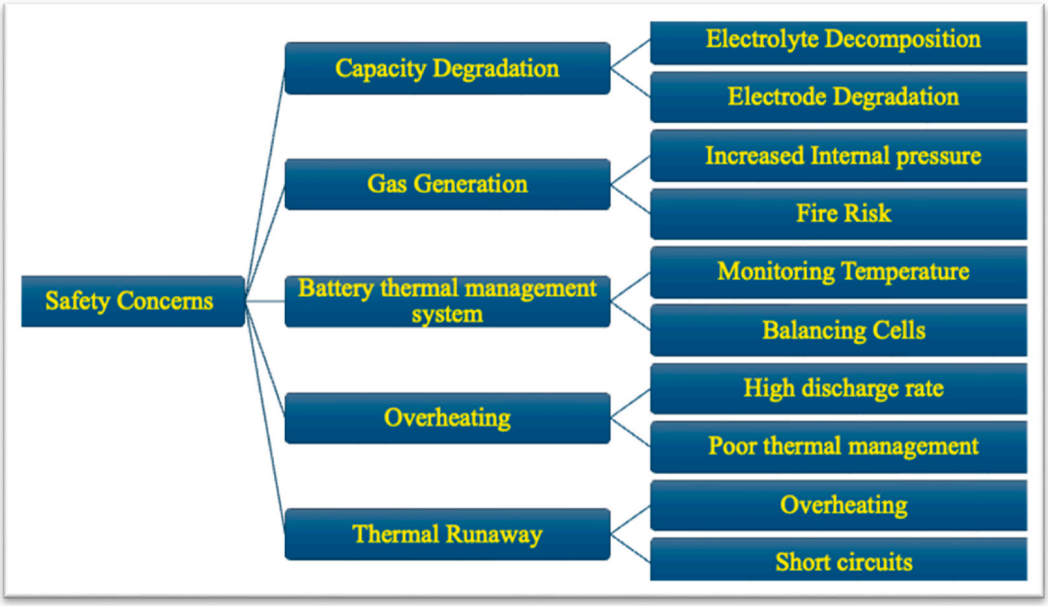
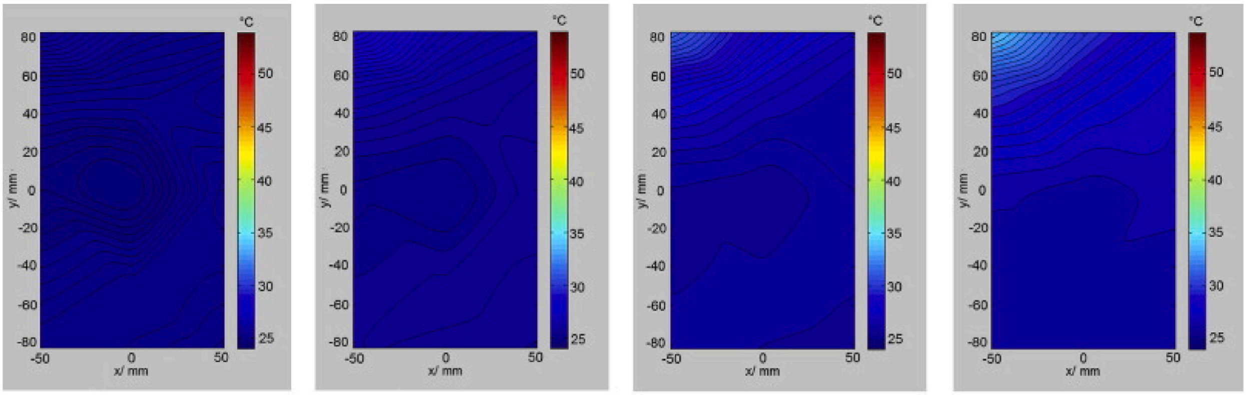
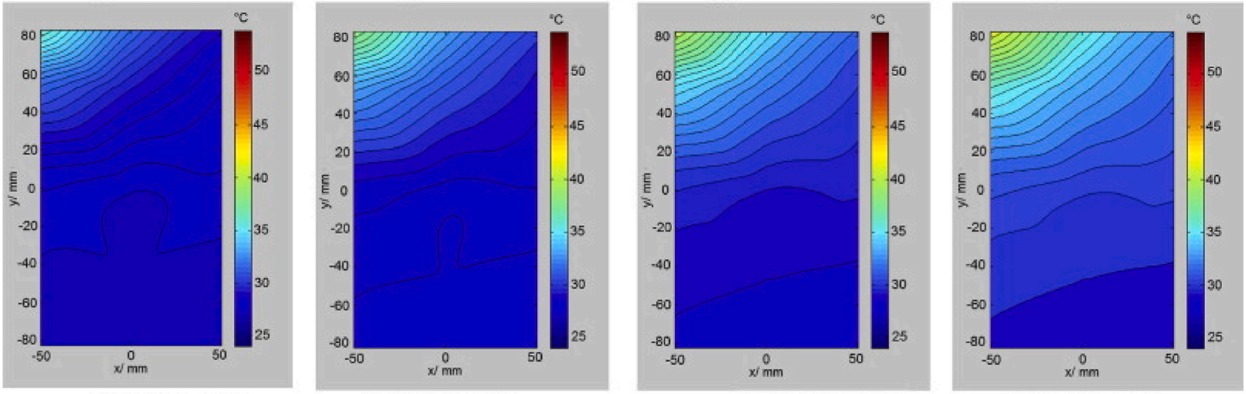


Fig. 4. General safety concerns in Li-batteries.



(a) DOD=0% (b) DOD=4% (c) DOD=8% (d) DOD=12%



(e) DOD=16% (f) DOD=20% (g) DOD=24% (h) DOD=28%

Fig. 5. (a–h): The decrease in size of the cold region to the left of the cell's center during adiabatic discharge at 1.5 C (Reproduced with permission from Journal of Power Sources Volume 241, November 1, 2013, Pages 536–553. Copyright © 2013 Elsevier B.V. [20]).

one electrode to another through current collectors, which also function as a base for electrochemically effective electrode materials.

2.1.3. *Thermal capacity of Li-batteries and thermal enhancement*

Li batteries are high-capacity holders and exhibit high performance owing to their high energy density (approximately up to 705 WhL^{-1}) and power density (approximately up to 10,000 WL^{-1}). Li batteries, which can be recharged, are nowadays used as power sources in several devices. Lithium-ion batteries' performance is severely hindered by extreme temperatures, which also restricts their usefulness. And the adverse consequences vary subject to the environmental temperature. The effective management of lithium-ion batteries requires accurate temperature monitoring within the batteries and a knowledge of the impacts of temperature. A review of how lithium-ion batteries fare in both cold and hot environments and the methods for measuring the interior temperature of lithium-ion batteries are described in Refs. [13–17]. Research shows that 97 % of the test time, the battery's interior temperature differential is less than 1 °C, and during thermal runaway, it reaches a peak of around 520 °C, see Fig. 3. During the examination, the battery's voltage is also measured. The time it takes for the temperature to spike from zero after a sudden decrease in voltage is 15–40 s. Such a lead period helps detect the onset of thermal fugitive. The internal resistance is calculated by dividing the pulse voltage by the pulse current during the ARC test, yielding a charge/discharge profile. After a gradual increase from 20 m to 60 m, the battery's internal resistance jumps to 370 m during thermal runaway, indicating that either the separator's integrity has been compromised or the battery has swollen [18].

2.1.4. *Life-span of Li-batteries*

The lifespan of Li-batteries is a key factor that distinguishes them from other types of batteries. When comparing the lifespan of Li-batteries to other battery chemistries, several factors must be considered, including cycle life, calendar life, performance degradation, and the specific application in which the batteries are used, following comparative analysis is prepared from above literature. A detailed comparative analysis based on the understanding of literature is provided in Table 1.

2.1.5. *Safety concerns in Li-batteries*

The operation of lithium-ion (Li-ion) batteries presents several primary safety concerns, especially related to temperature management. Understanding and addressing these concerns is crucial for the safe and efficient use of Li-ion batteries in various applications. Here are the main safety concerns given in Fig. 4.

Knowing the interior temperature of a battery helps to study thermo-electrochemical processes, check the accuracy of simulation mechanisms, and make improvements to the battery's thermal scheme. In an experiment, a 25 Ah laminated lithium-ion battery was outfitted with 12 thermocouples placed in carefully selected positions. Twelve more thermocouples were fixed to the surface in similar positions. At a range of discharge rates and in a variety of thermal environments, temporal and spatial temperature fluctuations were observed. Further, it was examined how these areas react to heat and cold. It was observed that to begin, even with a thin laminated cell, there might be a temperature difference of up to 1.1 °C between the inside and outside. Second, the thermal response time constants indoors were often several seconds longer than they were outside. Third, under an adiabatic 1.5 C discharge, the in-plane heat conductivity varied by more than 10 °C, which is substantially more than the through-plane fluctuation. The authors concluded that forced convection is a reliable method for minimizing both the average and the standard deviation in temperature. This work opened the path for implanting sensors/microchips in one cell to extract numerous physical-electrochemical signals concurrently by the direct monitoring of internal temperature [19,20]. Generally, the positive tab was found to be in the hot zone, while the negative tab was positioned at base of cell in cold zone. Furthermore, the temperature dissemination gradient was observed to follow a linear pattern from the center of heated zone toward cold zone. In other scenarios, the areas with higher temperatures were seen as two concentric circles inside the boundaries, positioned near positive terminal and towards the lower right of cell's midpoint. During the adiabatic discharge at a temperature of 0.3 °C, a steady region of lower temperature was seen to develop towards the left side of the cell. As the discharge rates, such as 1.5 C, increased, the cold zone underwent a gradual compression during the first stages of discharge, leading to a reduction in its size until it ultimately disappeared. **Fig. 5(a–h)** depicts the temperature distribution observed during a 1.5 C adiabatic discharge, providing a visual representation of the progressive shrinkage of the cold zone [20]. Table 2 presents the immediate manifestation of the most significant fluctuation (↔ = seen at the conclusion of discharge, whereas others occur at certain levels of discharge depth).

Internal heat production, thermal conduction, and heat dissipation in individual batteries lead to the development of temperature gradients on both the module and pack levels. One major problem that must not be overlooked is the emergence of temperature gradients inside battery packs. The monitoring of a battery's temperature is one such difficulty [21]. Over(dis)charging, high current

Table 2
The instantaneous occurrence of highest variation (↔ = at the end of discharge, others in particular DOD = DEPTH OF DISCHARGE, DR = DISCHARGE RATE, AD = ADIABATIC, NC=NATURAL CONVECTION, FC=FORCED CONVECTION), (Reproduced with permission from Journal of Power Sources Volume 241, November 1, 2013, Pages 536–553. Copyright © 2013 Elsevier B.V. [20]).

DR at °*C*	AD (DOD in %)	NC (DOD in %)	FC (DOD in %)
0.3	50	35	↔
0.5	50	35	55
1	↔	↔	50
1.5	50	50	50

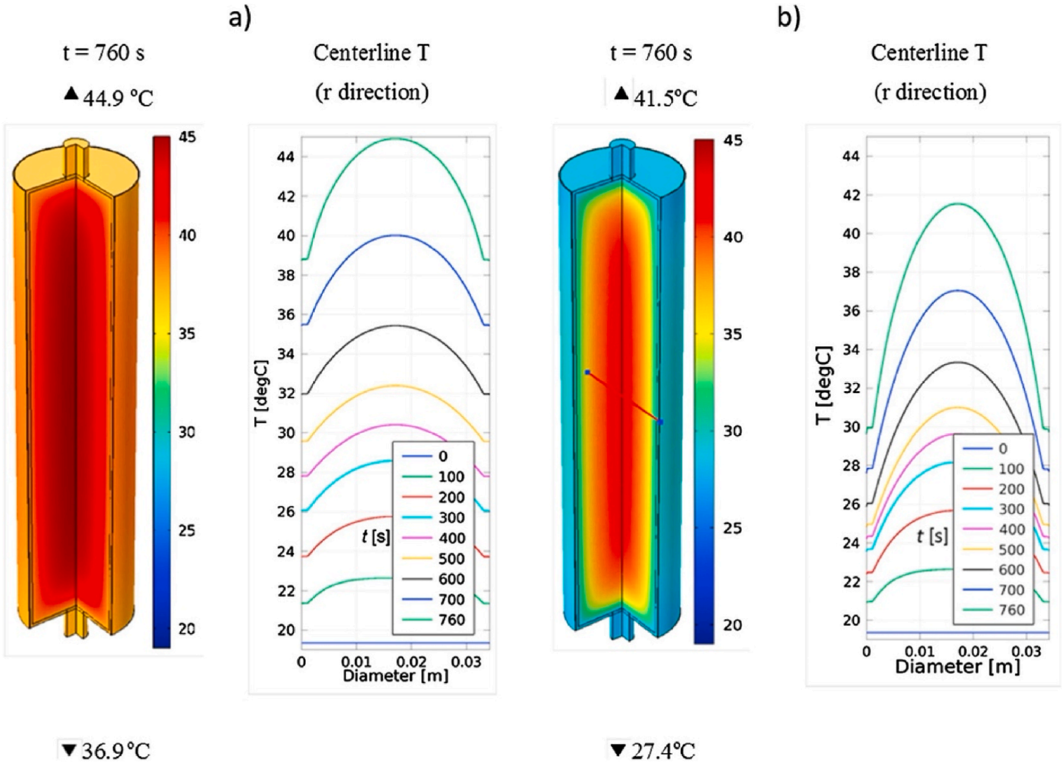


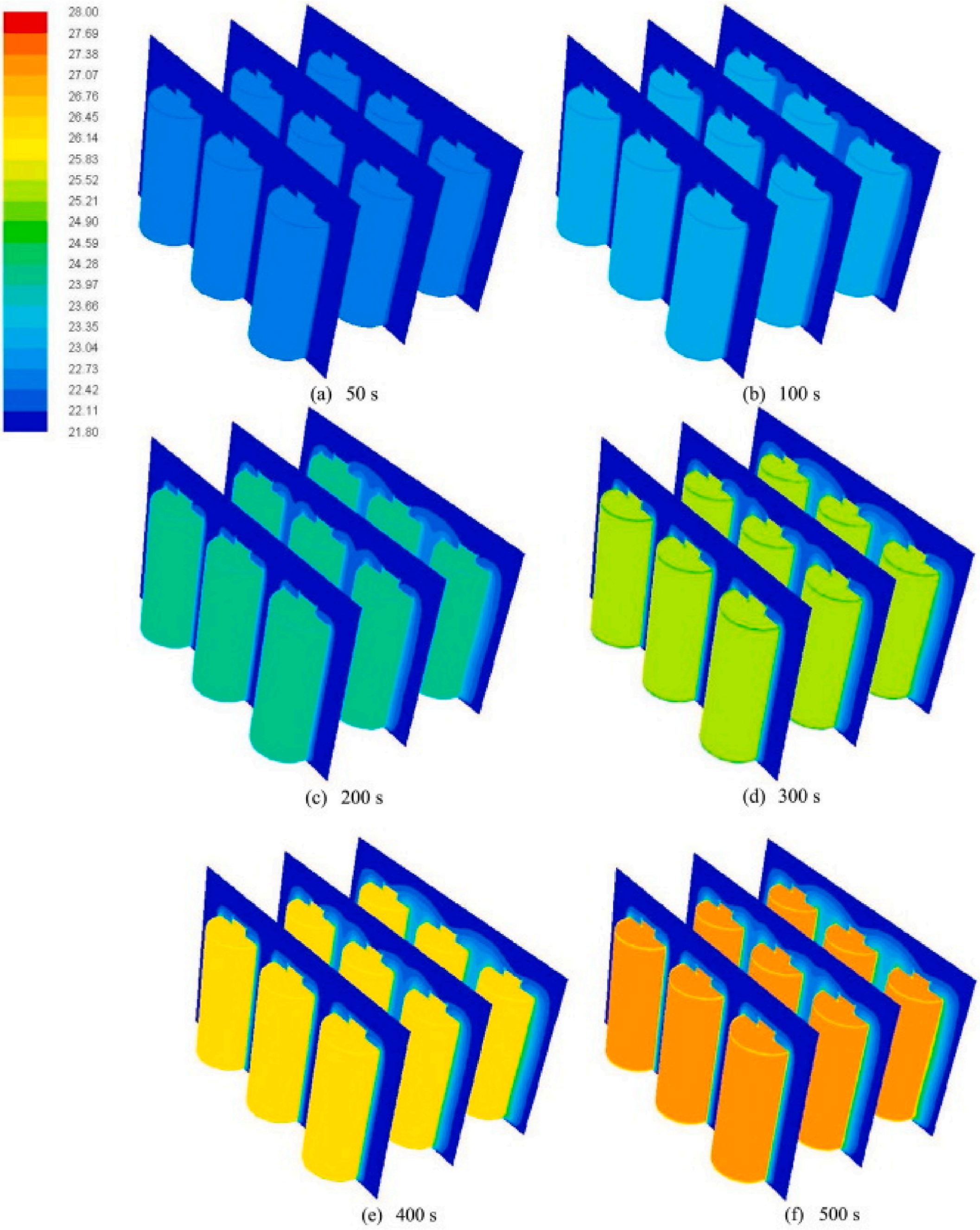
Fig. 6. (a–b): Here we see examples of (a) natural convection and (b) forced convection in thermal simulations of a 7.5 Ah cylindrical battery discharging at 6C (Reproduced with permission from Applied Energy Volume 240, April 15, 2019, Pages 918–945. Copyright © 2019 Elsevier Ltd. [12]).

loads, and short-circuiting all cause significant internal heat to be produced. As a result, batteries may become hotter than what would be indicated by just measuring their surface temperature. Fig. 6(a and b) displays the results of a thermal simulation experiment conducted on a cylindrical (high power) 7.5 Ah battery discharging at a rate of 6 C. The temperature within the battery is much greater than it is on the outside. Therefore, the performance, lifetime (SoH), and safety of Li-ion batteries may all benefit from increased internal temperature monitoring [12].

2.2. *Battery thermal management system (BTMS)*

Temperature variation of electric batteries is monitored by the BTMS and measured for use in experiments. Based on where the temperature sensors are placed, there are three distinct approaches to measuring battery temperature. First, each cell's temperature sensor is placed outside the cell. Most current approaches for commercial electric battery packs (such as that of a 2010 Toyota Prius) employ a single temperature reading from the cell's surface to reflect the cell's health [22–25]. Sensors in the cooling system (on the GM-Volt) or atop the sub-modules (on the Tesla Roadster) help determine the battery pack's multi-point temperature distribution in addition to monitoring individual cells' temperatures. There is no temperature sensor between the electrodes, although two have been claimed to be placed on top of the cell and sealed within. As a result, it's unclear whether the interior temperature is even being measured. However, it is hard to determine how the temperature within the cell is distributed using just a single sensor. Both techniques use an extra electrode temperature reading to determine overall cell temperature. The inaccuracy may be minor for the tiny cells used in consumer electronics like smartphones and laptops. With a large-format traction battery, however, internal temperature variations mean that surface temperatures no longer accurately reflect the battery's health. Local hot spots may emerge under highly nonuniform temperature distribution, which might reduce cell longevity and possibly set off safety issues.

The next step involves placing the temperature sensors deep into the cell. Knowledge of the interior temperature of a battery helps locate internal hot spots and zones, understand how heat builds up, and optimize thermal design of cells in terms of their shape (cylinder, prismatic, or laminated), capacity, and arrangement of critical parts like tabs. Not only does knowing the inside temperature of a cell aid with its design, but it's also necessary for properly validating thermo-electrochemical simulation mechanisms. The present battery modules are already rather complex, able to characterize the voltage, current, temperature, and Li-ion concentration in each electrode layer separately [26–28]. However, these models are often validated simply using the surface temperature at a single site. Due to insufficient data, the model's validity cannot be fully established, casting doubt on its reliability in making predictions. Despite the vital need to know one's body temperature, attempts to do so are uncommon in published works, perhaps because it is difficult to



(a) 50 s

(b) 100 s

(c) 200 s

(d) 300 s

(e) 400 s

(f) 500 s

Fig. 7. (a–f): TTR battery module ($T_\infty = 22\ ^\circ C$ & air velocity = 0.1 m/s) (Reproduced with permission from Engineering Science and Technology, an international journal Volume 21, Issue 5, Oct 2018. Copyright © 2009 Elsevier B.V. [29]).

introduce sensors into a single cell. A new generation of environmentally friendly transportation alternatives to gas-powered vehicles has just surfaced: electric vehicles (EVs) and hybrid electric vehicles (HEVs). Furthermore, the high energy density of Li-ion batteries makes them a good choice for EVs and HEVs. In high battery discharging situation, there is a large rise in battery temperature and non-uniform cell temperature. For instance, Jilte and Kumar [29] investigated cooling performance of the battery module at a constant current discharge rate of about 6.94 C (25 A). The study reports that the battery module's two side walls were left completely open to allow cooling material to enter and exit, resulting in improved heat dissipation. It was thought that larger inter-cell spacing would allow for adequate cooling air circulation and gas evacuation from the batteries. Using a user-defined function (UDF), the authors were able to replicate heat production in the battery cell during the discharge process. This research delved into the various thermal regimes, flow fields, and three-dimensional transient thermal responses that have been established inside the battery module. The localized hotspots are shown by areas where the air temperature increases to 7 °C. Even under conditions of low cooling airflow and high discharge rate, the examined BTMS keeps the battery temperature below 28 °C and the highest cell-to-cell temperature non-uniformity below 0.11 °C. The TTR (Transient Thermal Response) of subject module can be seen in Fig. 7(a–f).

To determine the interior temperature of a cylindrically designed 26650 lithium iron phosphate battery, Christophe Forgez [30] developed a plug-in testing technique. The battery's interior temperature was determined by inserting a T-type thermocouple into hole bored the cylinder's top. Several precautions were taken to ensure the operation's success. First, everything was done within an argon glove box to prevent contamination; second, the battery was almost completely depleted before drilling began. After inserting thermocouple, the hole was sealed with glue.

In response to extensive demand from the electric vehicle and renewable energy sectors, the world's lithium battery business is expanding at a breakneck pace. However, when businesses must rely on fewer suppliers for essential inputs, they open themselves susceptible to the risks of market price swings and unbalanced growth in the local supply chain. High prices for inputs, varying quality, and imbalanced supply and demand are among the problems that become crucial to solve. For the last five years in a row, the world has used more Li-ion (lithium-ion) batteries as compared to any other type, underscoring their dominant position in the global energy storage domain. The inefficiencies such as asymmetrical supply chain development, supply and demand mismatch, local protectionism, and quality variances are impeding the sector's healthy development, may hinder the development of businesses like new energy electric vehicles (NEVs) by making battery supply constraints more severe [31,32]. The world is continuously bolstering the under-resourced sectors, quality-control oversight, and fostering cooperation among market participants. Concerning the above facts, we find that a lot is still required to be done in this industry to have sufficient power resources [33].

2.3. Phase change materials (PCMs) and nano-enhancements

In view of PCM-based BTMS, their superior temperature control performance are recognized much recently. It was first suggested by Hallaj and Selman et al. [31,34], to use PCM in BTMS. The heating range of the PCM-cooled battery was narrower than that of the uncooled battery, as shown experimentally. Paraffin (PA), a popular PCM, however, has inherent flaws that need improvement, including poor heat conductivity and a propensity to leak. Considering PA's poor thermal conductivity, Goli et al. [35,36], created a composite PCM with graphene filler to increase the material's thermal conductivity. When 1 wt% graphene filler was added to conventional PA, the heat conductivity increased by a factor of 60. To shield PA/expanded graphite (EG) composite materials, Wu et al. [37], decided to use copper mesh (CM) as a sort of composite PCMs for BTMS. The porous nature of EG allows it to absorb liquid phase PA and prevent leakage, while the skeleton provided by CM helps to increase the module's heat conductivity and robustness. The testing findings demonstrated that the temperature uniformity and heat dissipation performance of CM/PA/EG was better than those of PCM without CM. The CM heat sink amalgamated in the composite PCM not only jested a crucial role in heat dissipation but also boosted the heat transfer competencies by disrupting the airflow under the unique circumstances of forced convection. In BTMS, EG/Kaolin/PA was employed as the PCM by Zhang et al. [38]. They discovered that a composite PCM made up of 10 % EG, 10 % Kaolin, and 80 % PA was the most effective in maintaining a constant temperature. With a discharging rate of 4 C, the peak temperature of a single cell could be efficiently measured below 45 C, and even under the harsh circumstances of a higher discharging rate, the temperature differential between each cell could also be managed within 5 C. The thermal management test lasted 30 min at 60 °C and found no evidence of leakage. The composite material can strongly reduce the temperature of the battery pack by 2.57 °C. Battery pack and cell temperatures may be greatly lowered after phase shift through PCM. The obvious situation in which PCMs are involved in battering packing and the ensuing temperature regulation is shown in Fig. 8(a and b).

As PCM undergoes phase shifts over a narrow temperature range, it stores latent heat that may be used to mitigate the buildup of heat inside the battery. Changes to PCM's chemical composition allow for fine-tuning of the material's melting point and temperature range of operation as a heat absorber. Specific values for the thermal conductivity, K, of common PCMs at room temperature (RT) are in the range of 0.17–0.35 WmK^{-1}. The RT thermal conductivity of silicon is ~145 WmK^{-1}, whereas that of copper is ~381 WmK^{-1}. Instead of conducting heat away from the battery pack, PCMs store it. In addition to preventing the Li-ion cell from overheating, using

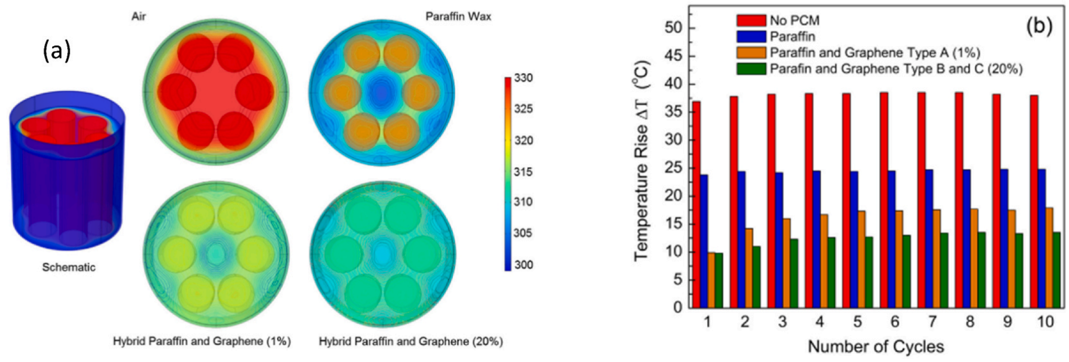


Fig. 8. (a–b): Numerical modeling of temperature escalation inside the Li-ion battery packs (Reproduced with permission from Journal of Journal of Power Sources 248, Feb 2014, Pages 37–43. Copyright © 2014 Elsevier Ltd [36]).

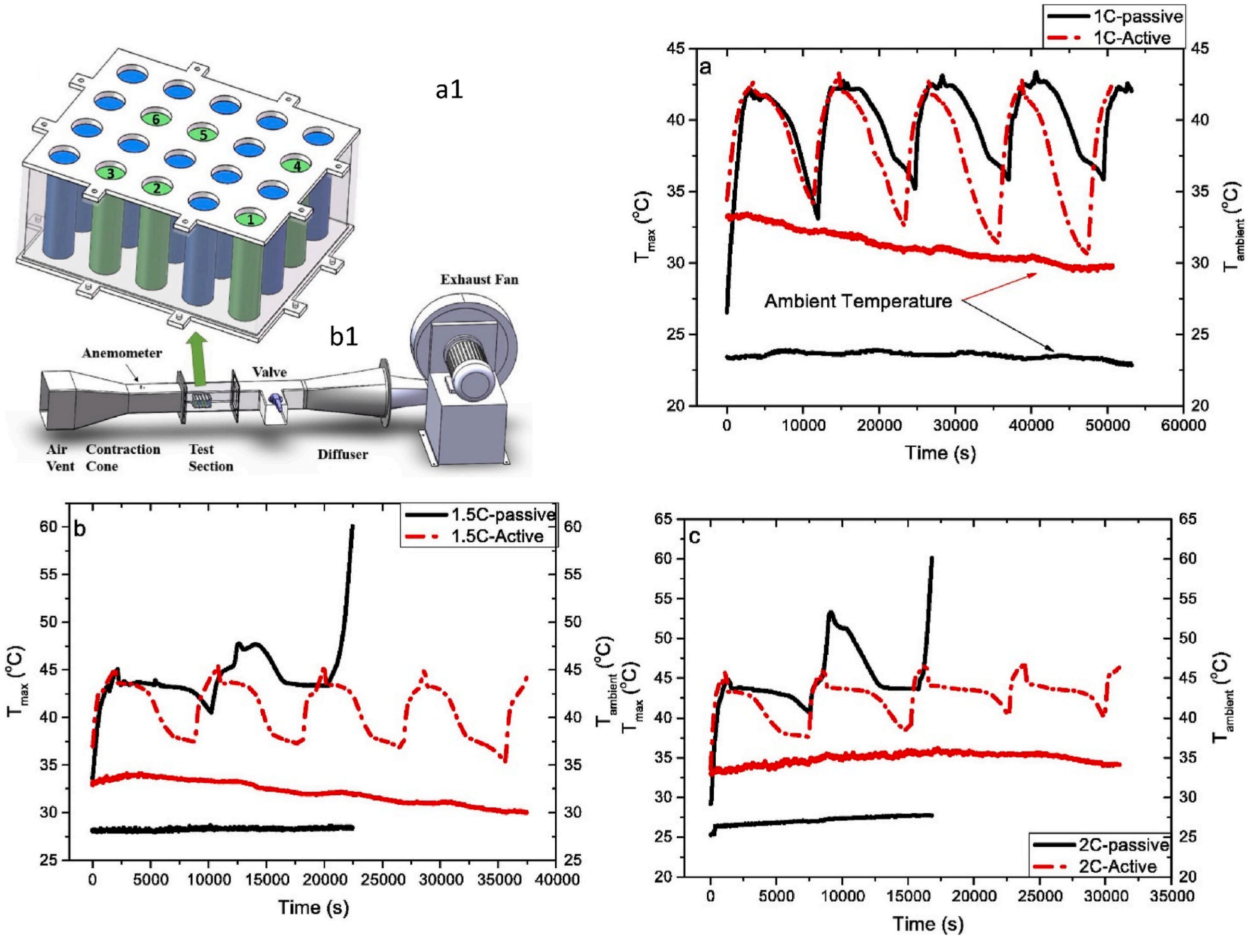


Fig. 9. (a1) Schematic of battery pack 5S4P; (b1) structure of the air channel. (a–c) Maximum battery temperature under both the fully passive and the hybrid systems (PCMs and forced air convection/discharge rate) of thermal management (Reproduced with permission from Applied Energy Volume 148, June 15, 2015, Pages 403–409. Copyright © 2015 Elsevier Ltd. [40]).

PCM in battery cells acts as a temperature buffer. This method differs from the standard practice of cooling computer chips. Thin layers of Thermal Interface Materials (TIMs) are employed to transport heat from computer chips to heat sinks and external packaging. TIMs have a thermal conductivity of about 1–25 $\mathrm{WmK^{-1}}$, whereas solid graphite-based heat spreaders may have a conductivity of over 10^3 $\mathrm{WmK^{-1}}$. Some researchers focused on variables outside of PCM's fundamental features while trying to improve it. The purest PCM material still has a major impediment to future use due to its poor heat conductivity. The effect of PCM breadth on the temperature of PCM-wrapped batteries was investigated by Javani et al. [39]. Results discovered that when the battery was charged and discharged at different power densities at 21 °C, the PCM thickness of 3 mm resulted in a more uniform temperature distribution and that the PCM thickness of 12 mm resulted in a 3.04-degree Celsius decrease in the highest temperature. The presence of PCM would be the key factor in moderating the battery's temperature rise in the first 7 min, and PCM with a larger thickness around the battery may offer improved cooling. Ling et al. [40] investigated the effectiveness of PCM-based composite BTMS with forced air cooling and compared its performance to that of PCM-based composite BTMS through natural air cooling. According to the results, PCM heated up in extreme scenarios like hyperthermal environments due to poor natural air cooling, and it was tough to properly export heat outside of it. The later experiment paired PCM with a forced air-convection method, and it was shown that the matching BTMS could maintain a maximum battery temperature below 50 C, at any rate, less than 2 C, even when the ambient temperature was 7 C greater than the battery temperature. In BTMS, PCM and forced air convection each served separate purposes. Some findings are shown in Fig. 9(a1, b1, a-c); PCM was cooled by forced air convection and kept under control of the ceiling and differential temperatures.

Using a liquid cooling system in conjunction with nano-enhanced phase change materials (NEPCMs) for battery modules offers numerous advantages that can significantly enhance the thermal management, safety, and overall performance of batteries. Liquid cooling systems provide a high heat transfer coefficient, allowing for efficient heat removal from battery cells. When combined with NEPCMs, the system can handle high thermal loads more effectively. The liquid coolant circulates through the battery pack, absorbing heat and transferring it to an external heat exchanger. NEPCMs absorb excess heat during peak loads and release it gradually, preventing temperature spikes [41]. Ensuring uniform temperature distribution across all battery cells is crucial for performance and longevity. Liquid cooling systems in conjunction with NEPCMs achieve this more effectively. The liquid coolant maintains a steady-state temperature, while NEPCMs mitigate local hot spots by absorbing and redistributing thermal energy [42]. Managing thermal stress effectively leads to prolonged battery life. Combining liquid cooling with NEPCMs reduces thermal degradation. The continuous cooling effect of the liquid system prevents excessive thermal cycling, while NEPCMs absorb and mitigate transient thermal spikes, reducing overall stress on the battery cells [43]. Efficient thermal management reduces the risk of thermal runaway, a critical safety concern in battery systems. Liquid cooling combined with NEPCMs enhances safety by effectively managing high temperatures. The liquid cooling system continuously removes heat, while NEPCMs act as a thermal buffer, absorbing excess heat during abnormal conditions and preventing temperatures from reaching dangerous levels [44,45]. Maintaining optimal temperature ranges ensures better energy efficiency and consistent battery performance. The combined system enhances overall energy management. Liquid cooling systems maintain optimal operating temperatures, reducing internal resistance and improving charge/discharge efficiency. NEPCMs provide additional thermal management, reducing the cooling load on the liquid system [46]. Thus, integrating liquid cooling systems with nano-enhanced phase change materials provides a robust solution for thermal management in battery modules. This hybrid approach offers significant advantages in terms of heat dissipation, temperature uniformity, battery lifespan, safety, and energy efficiency. By leveraging the high heat transfer capabilities of liquid coolants and the thermal storage properties of NEPCMs, this combined system addresses the critical thermal challenges faced by modern high-power battery applications.

The ineffectiveness of a passive TMS is probably attributable to the low rate of heat transfer occurring between PCMs and the environment in which they are located. Most of the very small amounts of heat that are created by batteries during discharge are stored in PCMs as sensible heat. This kind of heat may be transferred to the surrounding environment via the low-efficiency air natural convection. PCM, on the other hand, retains most of the latent heat that is formed by high-current discharge since so much more heat is created. Because of inefficient air natural convection, latent heat is not completely released before the commencement of the subsequent discharge. This has a double effect: first, it lowers the amount of heat that may be stored, and second, it increases the temperature at which the subsequent discharge starts. After several discharging cycles, the thermal energy storage capacity is insufficient to deal with the higher heat flow from batteries, which fallouts to a quick depletion of latent heat and a rise in battery temperature that

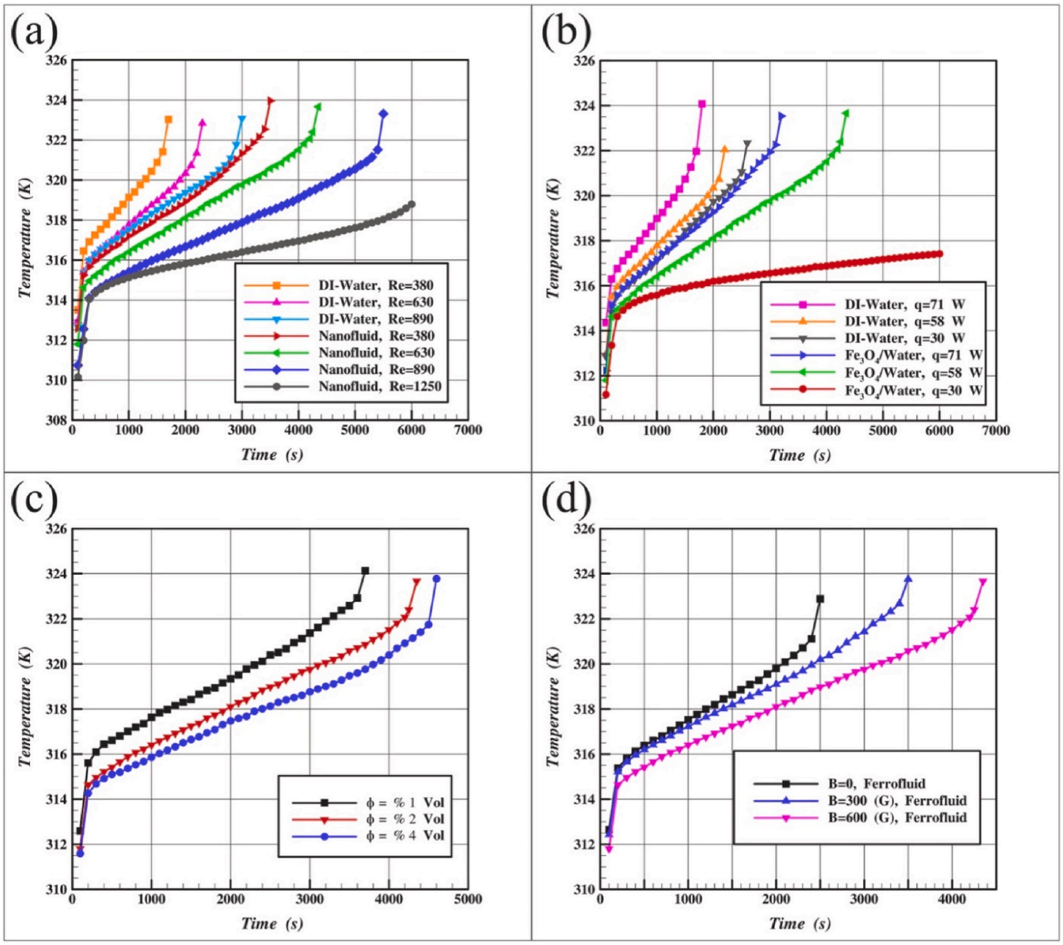


Fig. 10. (a–d): Various cases of temperature profiles (Reproduced with permission from Case Studies in Thermal Engineering Volume 28, Oct 2021, Pages 101539. Copyright © 2021 Elsevier Ltd. [76]).

is higher than the maximum permissible value [47–59]. In summary, nano-Enhanced Phase Change Materials (NEPCMs) significantly improve the thermal management of batteries compared to traditional PCMs through enhanced thermal conductivity, increased heat capacity, faster phase transitions, improved mechanical stability, and customizable properties. These improvements lead to more efficient heat absorption and dissipation, better temperature regulation, and extended battery life, making NEPCMs an advanced solution for modern thermal management challenges in battery systems.

2.4. *Challenges Associated with phase change Material (PCM) leakage*

Phase Change Materials (PCMs) are widely used in thermal energy storage systems due to their high latent heat capacity and ability to store and release large amounts of energy. However, PCM leakage poses significant challenges that can undermine the efficiency and reliability of these systems.

2.4.1. *Encapsulation issues*

Encapsulation of PCMs is a common method to prevent leakage. However, ensuring the integrity of the encapsulation materials over long-term thermal cycling is challenging. Encapsulation materials must withstand repeated melting and solidification without degrading or breaking. Failure in encapsulation can lead to PCM leakage, resulting in reduced thermal efficiency and potential damage to surrounding components. Sari et al. [60] highlights the importance of robust encapsulation materials to prevent leakage.

2.4.2. *Thermal expansion and contraction*

PCMs undergo significant volumetric changes during phase transitions. Thermal expansion and contraction can cause mechanical

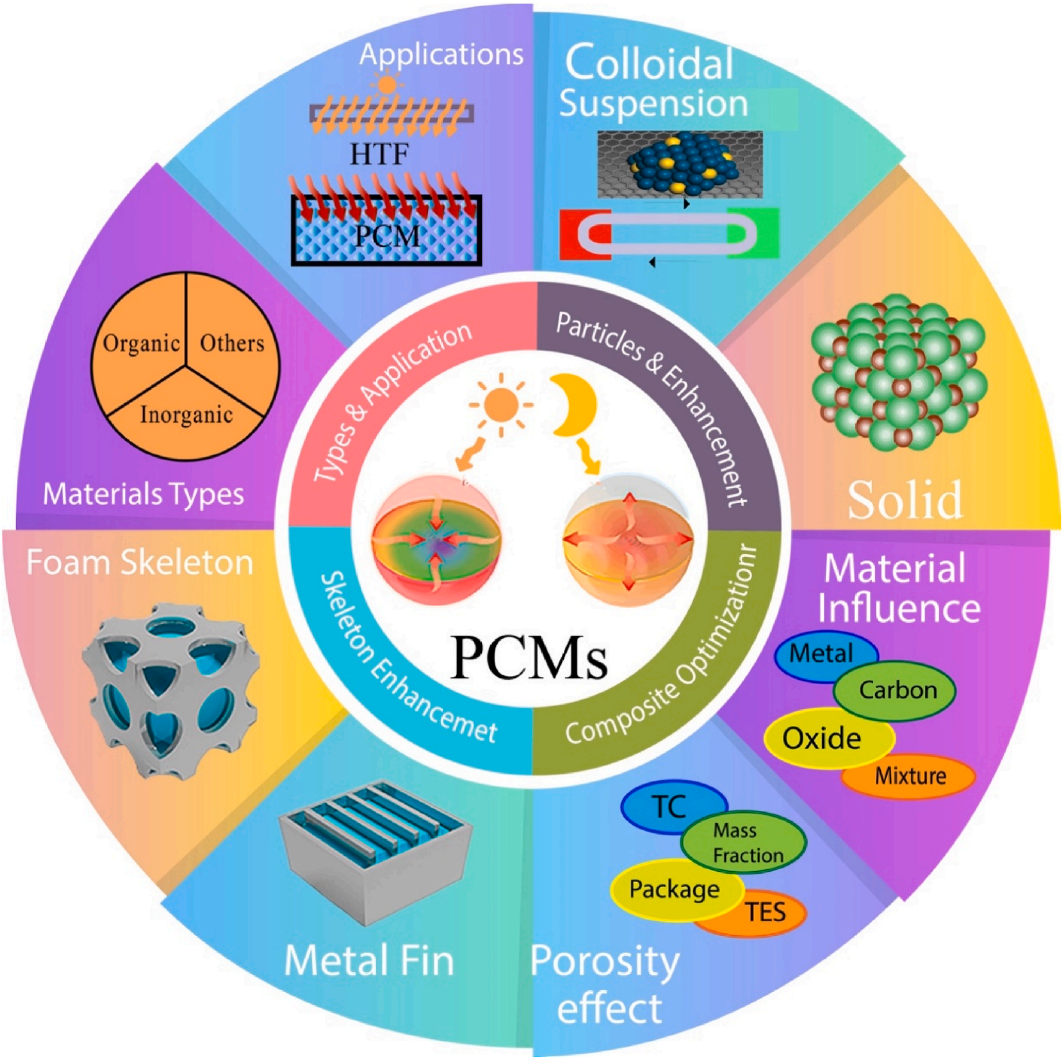


Fig. 11. Summary of the applications and practical scenarios of PCMs.

stress on encapsulation materials and containment vessels. Repeated thermal cycling can lead to micro-cracks and eventual failure of the encapsulation, resulting in PCM leakage. Zhang et al. [61] discuss the challenges posed by thermal expansion and contraction in PCM systems.

2.4.3. *Compatibility with containment materials*

PCMs must be chemically compatible with their encapsulation and containment materials. Incompatibility can lead to chemical reactions that degrade the encapsulation material. Chemical degradation can result in the breach of the encapsulation, causing PCM leakage and reducing the system's lifespan. Sarier et al. [62] presented research that emphasizes the need for chemical compatibility between PCMs and encapsulation materials.

2.4.4. *Structural stability*

The structural stability of PCM systems can be compromised by external factors such as vibration, mechanical impact, and environmental conditions. Physical damage to the encapsulation or containment system can lead to PCM leakage, necessitating frequent maintenance and replacements. Rashid et al. [63] reported a comprehensive review on these issues. This review discusses the structural stability challenges in PCM systems.

2.4.5. *Cost and complexity of high-performance encapsulation*

Developing high-performance encapsulation methods, such as microencapsulation or nanoparticle-enhanced encapsulation, can be complex and costly. The increased cost and complexity can limit the practical implementation and widespread adoption of PCM technologies in cost-sensitive applications. Khudhair et al. [64] analyzed this aspect in their review article. This review covers the cost implications of advanced encapsulation methods.

2.5. *Analysis of behavior and impact of enhanced PCM on Li-Battery*

Before attempting to identify methods to increase the safety of Li-batteries (LIBs), it is important to comprehend the mechanics of battery thermal runway (TR). As it stands, the primary cause of TR is the rapid increase in internal LIB temperature brought on by misuse or causes such as short-circuiting, overcharging, high-rate charging/discharging, and so on. Since LIBs often function as battery packs, each cell may be seen as a domino, and the TR process of the battery can be compared to the toppling of a set of dominoes. This means that a single battery's TR might trigger the TR of all the battery groups, leading to a fire accident, under the TR condition (called the Domino Effect). The TR phenomena include the battery discharging a lot of heat, injecting gas from the inside, combusting violently, or even exploding. Most fire incidents would happen if TR couldn't be managed in time. More and more researchers are

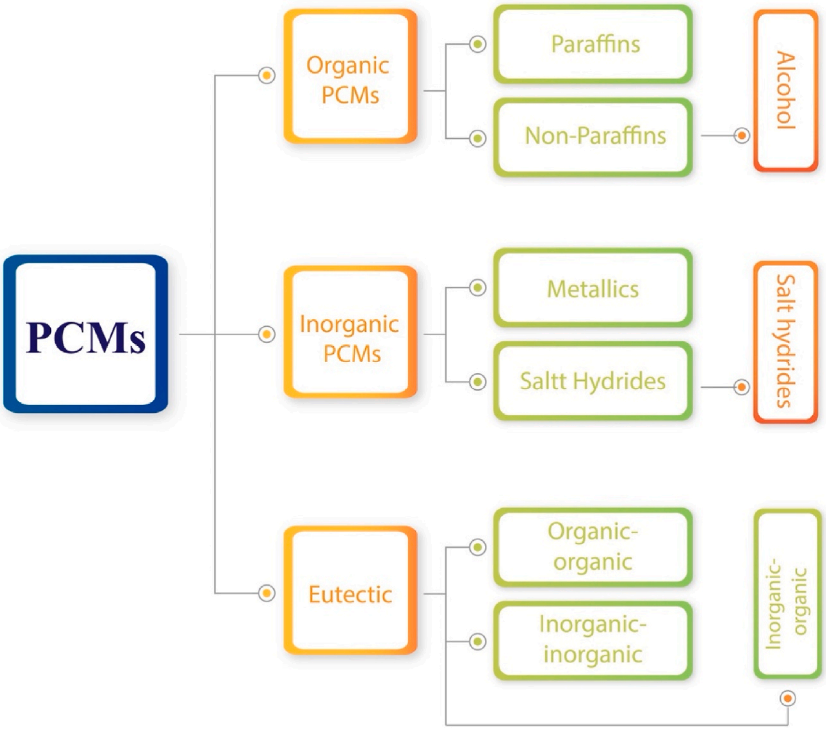


Fig. 12. Different classifications of PCMs.

focusing on the issue of TR during the use of LIBs because of its importance to the overall battery safety business. Consequently, research into a BTMS with high heat dissipation capability is required to ensure that the other batteries in the pack are safe in the event of a TR in one battery. There have been several studies conducted on the topic of heat dissipation management technologies [72–75]. A well-reasoned BTMS architecture is essential for enhancing LIB security and preventing performance decline. Different batteries have a more optimal temperature range to operate, but all of them need to be kept within a certain range for optimal electrochemical performance, battery life, and economic performance in EVs and HEVs. The impact of localized hot and cold spots on a battery bank must also be considered. PCMs are very efficient heat sinks, but they can't actively generate heat. In severe situations, including the scenario during high-current charging or discharging, or when the surrounding air is very hot, the thermal management systems may fail due to a lack of accessible latent heat. Kiani et al. [76], presented a novel TMS for pouch li-ion battery modules, with an emphasis on demanding environments. To make use of paraffin's high thermal capacity as a PCM, it was encased in a copper foam that included a heat sink that was cooled by air. When working within the recommended temperature range, the module provides excellent thermal efficiency for the battery pack, which is especially noticeable over long periods when the module is in operation. A battery surrogate was employed to replicate the heat produced by LIB during high continuous current discharge and the beginning of thermal runaway. Results of this simulation are shown in Fig. 10(a–d).

2.6. PCMs and their application in Li-batteries

Li-ion batteries are widely employed for their many advantages, including their low self-discharge rate, and high charge cycle count that requires minimal maintenance. Just like any other technological advancement, some drawbacks must be considered. Lithium-ion batteries (may catch fire if the separator is broken) have a short two-to-three-year lifetime after manufacturing and cannot be refilled once completely discharged. BTMS are devised continuously to help improve the battery life and working capacity of Li-batteries by maintaining the temperature rise. BTMS using PCMs is an effective technique of maintaining an optimal operating temperature for lithium-ion batteries. Still, improvements are needed to PCM's limitations especially poor thermal conductivity and heat dissipation. The BTMS may benefit from the integrated fins possessing enhanced ability to dissipate more heat. To recover the PCM latent heat, increasing air velocity may assist, but this application may require extra energy to operate the air-inflow [37,116–118]. Some important areas for PCMs are summarized in Fig. 11.

To cope with the power demand, the world has to depend largely on coal which is readily available and restricts the development of high-end technological developments for achieving carbon neutrality. PCMs-based BTMS is a technical bottleneck that has been focused on and breaking through for many years. Existing performance of Li batteries is direly dependent on their thermal performance. From the scientific and aesthetic point of view, the PCMs performance can be enhanced with addition of other metallic nanoparticles such as copper/copper oxide, alumina, and many other oxides of metals having higher thermophysical properties. Figs. 12 and 13 reflect the classifications, types and techniques for PCMs performance enhancement.

BTMS is a piece of equipment used to keep a battery's temperature within an acceptable range for operation. Liquid cooling BTMS requires complicated equipment to ensure the effect, whereas typical air-cooling BTMS not only demands more power but also cannot fulfill the need for modern lithium-ion battery (LIB) packs with a higher energy density. Therefore, BTMS based on PCMs is the current fashion [8,53,119]. By using PCMs to absorb sufficient heat, a battery pack's temperature may be maintained within the typical working range for extended periods of time without the need for additional power sources. Combining PCMs with high capacity of thermal conductivity fillers such as expanded graphite (EG) and metal foam, or coordinating with fins, might considerably increase the

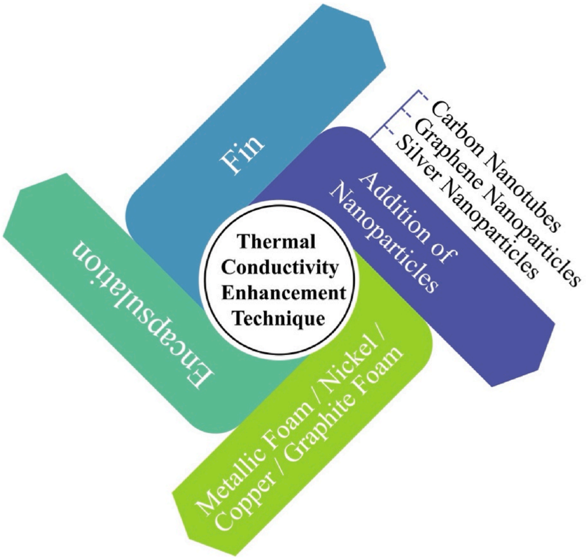


Fig. 13. Types and techniques to improve the performance of PCMs.

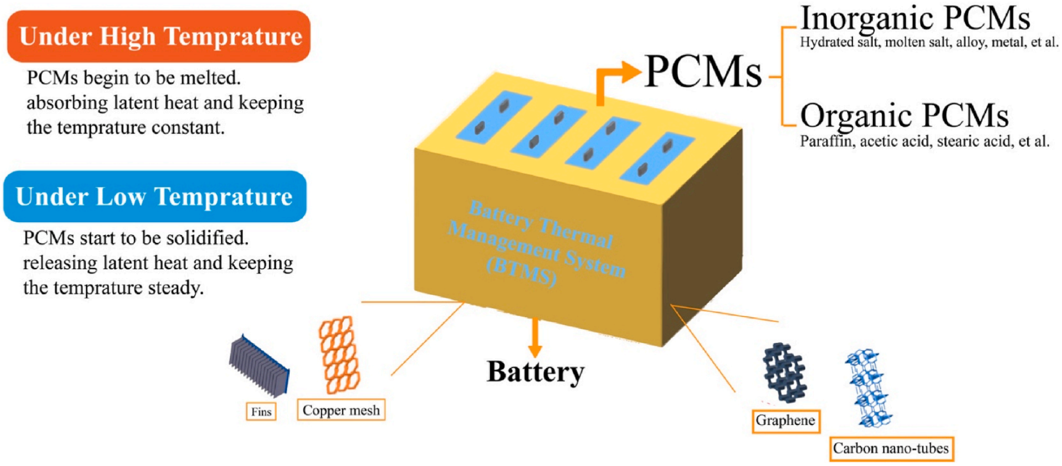


Fig. 14. BTMS scenario using nanomaterials such as; Graphene and Carbon nanotubes.

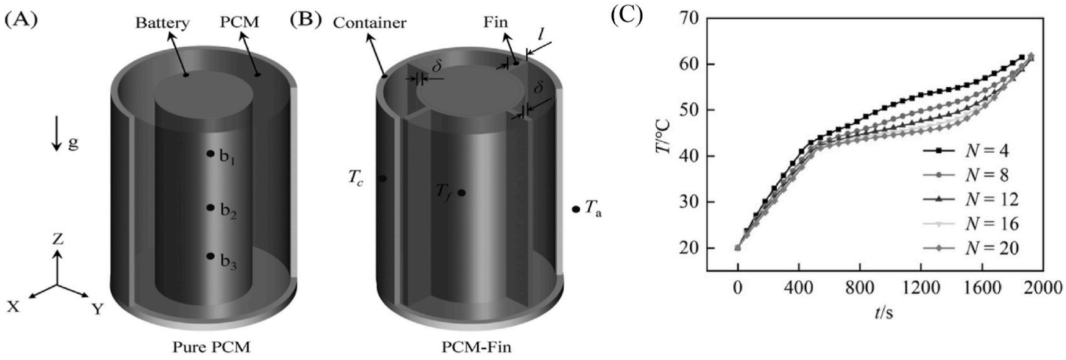


Fig. 15. (A–B) Schematic of fins structure and (C) Temperature evaluation for different fin numbers (Reproduced with permission from International Journal of Energy Research Volume44, Issue9 July 2020 Pages 7617–7629. Copyright © 2020 John Wiley & Sons Ltd. [82]).

heat dissipation efficiency of BTMS. The BTMS working concept of PCMs with thermal conductivity enhancement techniques like adding fins and fillers is given in Fig. 14.

Thermal management systems of batteries must be sufficient to control energy loss, reduce carbon emission, and be capable of long-run heat and thermal energy storage and to help in gaining a longer battery life. Compared to metal oxide nanoparticles, CNTs are quite pricey despite their efficacy in improving the PCM's thermal properties. On the other hand, Alumina, and copper for finned installed coating of Li-batteries may provide similar results with the addition of more percentages (up to 2 % or more), which can be cheaper than CNTs [33,116,121].

2.7. Analysis of metallic fins involvement in BTMS

PCMs' poor thermal conductivities support their low heat transfer rates during the cycles of charging and discharging. Hence, thermal conductivity enhancement (TCE) techniques are very important to analyze the capability of PCMs. Multiple fin designs, micro or macro encapsulation, and insertion of higher conducting material or particles (such as carbon nanotubes, metallic rings, carbon matrices or graphite brushes, and chips [77–80]) are all examples of these techniques. The purpose of each technique is to boost the effective heat conductivity or the area of heat exchange. An intriguing overview of the possible heat transfer rate improvements of several TCE systems is presented by Tian et al. [81]. Following the idea of TCE, the involvement of fins in PCM-based structures received much attention. Zheng et al. [82], proposed for cylindrical lithium-ion batteries, a new phase change material (PCM) system with added fins. The efficiency of the systems when discharging was investigated via experimental testing. When compared to a system without fins, the PCM-Fin system's operational time is enhanced to 75 %, 68 %, and 61 % when the heat generation rate is 10 W, 12.5 W, and 15 W, respectively. The impact of the fins' thickness, length, and number as well as their material (nylon, steel, Al-alloy, titanium, and copper) on thermal performance was investigated by ANSYS Fluent simulations. To evaluate performance, a function was created that considers both thermal performance improvements and system weight increases. According to the findings, the optimal configuration for Al-alloy fins is 8 in number, 7.5 mm in length, and 0.5 mm in thickness. Additionally, for a heat transfer coefficient of 5, 10, 15, and 20 $Wm^{-2}K^{-1}$, respectively, the PCM-Fin system operates for 2150 s, 2490 s, 2940 s, and 3570 s, an increase of 14 %, 32

%, 56 %, and 90 % over the adiabatic condition, (see for example Fig. 15(A-C)).

Fan et al. [83] investigated passive BTMS using PCMs for lithium-ion batteries. The work involved a PCM system for battery thermal control that couples metal fin intensification using numerical analysis to look at how various design parameters, including metal fin diameter, PCM thickness, and number of fins can affect the proposed BTMS's performance. According to the results, the maximum battery temperature is reduced by 18.6 % using the unique hybrid BTMS, whereas it is reduced by just 3.2 % using PCM-BTMS without involving fins. Battery and PCM may benefit from better heat dissipation because of the fins that are built right in. Maximum performance is achieved with a 1.0 mm PCM thickness, 162 number of fins, and a 3.0 mm fin diameter. By using less energy, this ideal layout keeps battery temperatures down to where they should be, about 40 °C.

3. Enhanced lifespan and performance of Li-battery modules

Hybrid and ternary battery modules, which integrate different materials and chemistries, have been extensively researched and developed to enhance the lifespan and performance of Li-ion batteries. Hybrid and ternary battery modules leverage the strengths of multiple materials to create a balanced electrochemical system. According to the study by Nitta et al. [84], NCM (Nickel Cobalt Manganese) cathodes provide an excellent balance between high energy density, thermal stability, and cost-effectiveness, which is crucial for improving battery lifespan and performance. Effective thermal management is critical for battery longevity. Research by Liu et al. [85] shows that hybrid systems with diverse material compositions distribute heat more evenly, reducing the occurrence of hotspots that can degrade battery materials and shorten lifespan. The structural stability of battery materials is a key factor in extending battery life. A study by Manthiram [86] highlights those ternary materials, such as those in NCM and NCA cathodes, exhibit superior structural stability during charge-discharge cycles, which mitigates capacity loss and prolongs battery lifespan. Customization is a significant advantage. Research indicates that hybrid and ternary batteries can be tailored to specific performance needs by adjusting material ratios, leading to optimized performance for various applications [87,88].

In addition, Battery-PCM and Battery-PCM-Fin systems were subject to cycling testing. One cycle was defined as 1000 s of heating followed by 1000 s of cooling by natural convection, and three cycles were tested. The pace at which the temperature in the Battery-PCM-Fin system enhances during cycle testing is substantially lower than that in the Battery-PCM system. For instance, with a heat production rate of 15W, simulating the rapid discharge rate of real-world batteries, battery surface temperature climbed beyond 60 °C after each heating phase, and it reached a maximum of 72.6 °C. During the testing, the battery surface temperature reached over 60 °C for a total of 2110s. First heating procedure for the Battery-PCM-Fin system resulted in a battery surface temperature of 56.3 °C. Battery surface temperature remained above 60 °C for only 1340 s, a drop of 12.8 % compared to the time spent in the Battery-PCM system, demonstrating the superior temperature control performance of the Battery-PCM-Fin system. Some relevant literature may be referred to the attempts [89–115]. From the above literature and understanding, we conclude that metallic fins play a crucial role in enhancing the performance of Phase Change Material (PCM) systems in Battery Thermal Management Systems (BTMS). Their primary function is to improve heat transfer efficiency within the PCM, ensuring effective thermal regulation of the battery pack.

1. PCMs typically have low thermal conductivity, which can limit the rate at which heat is absorbed and released during phase transitions. Metallic fins, made from materials with high thermal conductivity like aluminum or copper, significantly improve this by Increasing heat transfer area and facilitating rapid heat distribution.
2. Metallic fins aid in dissipating heat more effectively from the PCM to the surroundings, which is essential for maintaining the battery within its optimal temperature range. This is achieved by efficient thermal pathways and reduced thermal resistance.
3. By improving the thermal conductivity and heat distribution within the PCM, metallic fins help accelerate the phase change process by faster melting, solidification, and consistent phase change.
4. Metallic fins contribute to maintaining a more uniform temperature distribution within the battery pack, which is critical for battery performance and longevity for balanced heat absorption and minimizing hot spots.
5. Metallic fins also provide structural support to the PCM, which can enhance the reliability and durability of the BTMS.

4. Porous materials for use in NEPCMs and their impact on BTMS

Porous materials are widely used in NEPCMs due to their unique properties that significantly enhance thermal management. Wu et al. [122] discusses the enhancement of thermal conductivity in phase-change materials, highlighting the role of porous materials and nanomaterials in improving thermal management. Zhou et al. [123] reviewed and discussed the use of PCMs in building applications, emphasizing the importance of porous materials for effective thermal energy storage and management. Singh et al. [124] The study highlights the capillary effects in porous materials and their impact on the thermophysical properties of nanofluids, which are critical for NEPCMs. Lin et al. [92] reported a comprehensive review of such materials and their applications in industry. In this comprehensive review, the authors covered various aspects of thermal energy storage using PCMs, including the role of porous materials in enhancing thermal management. The paper discusses the enhancement of thermal properties of PCM through the addition of nanoparticles, showcasing the benefits of using porous materials in NEPCMs. Here are the key properties and how they contribute to improved thermal management.

1. Porous materials have a high surface area, which facilitates a larger contact area between the NEPCM and the heat source or sink. This enhanced contact area improves the efficiency of heat transfer during the phase change process. Faster and more efficient heat absorption and release during phase transitions, leading to better thermal regulation and stability.

2. Many porous materials, especially when combined with nanomaterials like carbon nanotubes or graphene, exhibit high thermal conductivity. This property helps in quickly spreading the heat throughout the material. Improved heat dissipation and uniform temperature distribution, preventing hotspots and enhancing the overall thermal management system.
3. Porous materials can facilitate capillary action, which helps in the even distribution of the phase change material within the pores. This ensures consistent performance of the NEPCM. Enhanced impregnation and retention of the PCM within the matrix, leading to stable and reliable thermal management over repeated cycles.
4. The structure of porous materials provides mechanical stability and maintains the integrity of the NEPCM. This is crucial for applications where the material undergoes repeated thermal cycles. Durability and longevity of the thermal management system, ensuring it can withstand numerous phase change cycles without degradation.
5. Porous materials can be easily integrated with various nanomaterials, which can enhance their thermal properties and phase change behavior. This synergy is vital for creating effective NEPCMs.
6. Enhanced thermal properties such as increased thermal conductivity and improved latent heat storage capacity, resulting in superior thermal management performance.

The global community is making concerted efforts to improve its energy issues and transition to a carbon-free economy. Due to its great energy density, the lithium-ion battery has become the primary energy storage component in all cutting-edge areas. However, there are still several obstacles to overcome when manufacturing large-scale Li batteries. The market affordability of the applications that use these batteries is weakened by their deterioration, instability at high temperatures, performance degradation at low temperatures, danger of overcharging and overcharging, and difficulties in fault identification and prognosis. Balancing batteries, implementing safe and efficient charge/discharge procedures, managing heat, identifying problems, and making predictions are all typical functions of battery management systems. Battery performance at the cell, module, and pack levels should increase with the introduction of advanced battery management systems. Temperature conditions influence the geometry of the battery, this might have an impact on the performance that was anticipated, or in the worst-case situation, it could cause damage and break. For these reasons, it is crucial to design cooling systems that transfer heat equally across all the elements that make up the system. On the other hand, it is important to limit the amount of heat sources as well [39,83,119,125,126].

5. Practical implementation techniques

Aiming at the influence of the used materials and working fluids' inefficiency, ANSYS-based finite volume scheme and COMSOL Multiphysics are frequently used to establish phase transitions of the nano-enhanced PCMs. These numerical schemes analyze the model in a contained boundary through meshing and constrained settings and boundary conditions. The components of BTMS mainly comprise the working fluid, the phase-changing materials, charging and discharging limitations, and melting temperature of PCM. Therefore, CFD models are adopted to study the changes appearing in all the parts subject to flow and phase transitions of PCM-based BTMS [55].

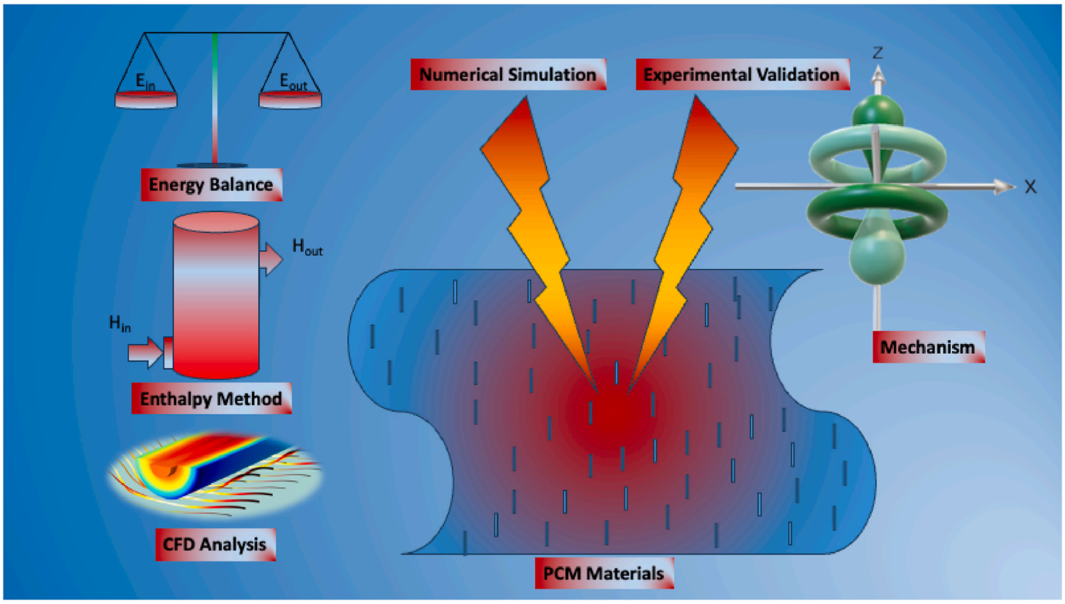


Fig. 16. Step-by-step working environment for CFD analysis.

5.1. *Basic assumptions for phase transition and heat transmission*

For PCM phase transition, some considered assumptions are: 1) Homogeneous and isotropic PCM. 2) Phase change happens within a temperature range. 3) Absence of wall pipe thermal resistance. 4) Laminar flow. 5) Base fluid is viscous and incompressible. 6) PCM thermal characteristics remain unchanged. Traditional mathematical modeling methods make it difficult to complete the flow field analysis under such complex conditions. Thus, 3D-CFD analysis after the parametric solid model of BTMS is constructed to examine the matching connection between the major geometric characteristics of BTMS and PCMs. The experimental platform must be simulated with appropriate simplifications.

Commercial software such as ANSYS Fluent, COMSOL Multiphysics, and others are used to mesh the calculation domain into grids based on grid independence verification and the computational efficiency-accuracy tradeoff. The simulations are then conducted using an enthalpy porosity formulation included in the software to make the control equations uniform for solid and liquid phases. The 3D double-precision, unstable solver, solidification/melting model, and minimized time step were utilized in the calculations (see Fig. 16). Owing to the literature, some basic techniques are summarized below.

5.2. *Experimental techniques to Enhance heat transfer in composite phase change materials (EPCM)*

Enhancing heat transfer in composite phase change materials (EPCM) is crucial for improving their thermal performance in various applications such as thermal energy storage and thermal management systems. Several techniques have been developed and studied to achieve this enhancement. Below are some key techniques along with references to relevant literature.

5.2.1. *Incorporation of high thermal conductivity additives*

5.2.1.1. Metal particles. Adding metal particles such as aluminum, copper, and silver to PCM enhances thermal conductivity due to the high thermal conductivity of metals. Improved heat transfer rate, leading to faster charging and discharging cycles. Zhang and Fang [65] revealed in their study, how the addition of metal particles to PCM enhances its thermal conductivity.

5.2.1.2. Carbon-based materials. Incorporating materials like expanded graphite, graphene, and carbon nanotubes significantly enhances the thermal conductivity of PCM. Enhanced thermal performance due to better heat distribution and improved thermal conductivity. Sari et al. [66,67] investigated the enhancement of thermal properties of PCM with the addition of expanded graphite.

5.2.2. *Embedding porous materials*

5.2.2.1. Metal foams. Using metal foams like aluminum and copper as supporting matrices for PCM. Increased thermal conductivity and structural stability, leading to efficient heat transfer. Yu et al. [68] reported a study on the incorporation of metal foams and other similar materials in porous structures. This research highlights how metal foams enhance the thermal conductivity of PCMs.

5.2.2.2. Silica aerogels. Silica aerogels provide a high surface area and porosity, which improves the thermal conductivity of PCM. Improved heat storage capacity and thermal cycling stability. Mitran et al. [69] provided a detailed review on the implementation and working capacity of these concepts. This study demonstrates how porous silica enhances the thermal performance of PCM.

5.2.3. *Microencapsulation*

Encapsulating PCM in micro-sized shells made of materials like polymers or metals. Increases the surface area for heat transfer, enhances the stability of PCM, and prevents leakage. Alkan et al. [70] discussed the thermal properties of microencapsulated PCM and its benefits for heat transfer.

5.2.4. *Use of fins and extended surfaces*

Incorporating metal fins and other extended surfaces within PCM to increase the heat transfer area. Enhanced heat transfer rate due to increased contact surface area between the heat source and PCM. Khanna et al. [71] reported a paper on involvement of fins in the multiple structures of energy storage. This study covers various techniques, including the use of fins to enhance heat transfer in PCMs.

The enhancement of heat transfer in EPCMs is crucial for their effective application in thermal management systems. The incorporation of high thermal conductivity additives, embedding porous materials, microencapsulation, use of fins, and development of form-stable composites are some of the key techniques that have been shown to significantly improve the thermal performance of EPCMs. Each technique has its unique advantages and can be selected based on the specific requirements of the application.

5.3. *Modeling and simulations*

5.3.1. *Mathematical modeling of PCMs*

The liquid PCMs are modeled as three-dimensional, unstable, laminar, viscous, and incompressible fluids. Conduction in solids and convection in liquids create heat exchanges in the computational domain. Disregard phase transition PCM volume fluctuation. These continuity, momentum, and energy equations (1)–(6) represent PCM behavior while charging and discharging [37,127–132].

a ***Continuity equation:***

$$\frac{\partial p}{\partial t} + div\left(\rho \overrightarrow{V}\right) = 0, \tag{1}$$

where ρ and $\overrightarrow{V}$ represent the density and velocity of the fluid.

b ***Momentum equation:***

$$\rho \frac{\partial \overrightarrow{V}}{\partial t} + \rho \overrightarrow{V}.\nabla\left(\overrightarrow{V}\right) = -\nabla p + \rho \overrightarrow{g}\left(T - T_{ref}\right) + \mu \nabla^2 \overrightarrow{V} + \overrightarrow{S} \tag{2}$$

where μ is fluid dynamic viscosity, p is pressure, $\overrightarrow{g}$ gravity vector and T temperature. The source term $\overrightarrow{S}$ can be defined as follows:

$$S = -\frac{(1-f)^2}{f^2 + \varepsilon} A_{mushy^{v}} \tag{3}$$

such that f refers to as fluid fraction, ε marginal constant to avoid the denominator becoming zero in certain cases and A_{mushy} is a constant of mushy zone.

c ***Energy equation:***

$$\frac{\partial(ph)}{\partial t} + \nabla.\left(\rho.h.\overrightarrow{V}\right) = \nabla.k(\nabla \mathrm{T}) \tag{4}$$

such that k is thermal conductivity, enthalpy h satisfying

$$h = \int_{T_{ref}}^{T} C_p dT + h_{ref} + fL \tag{5}$$

in which L and h_{ref} are latent heat of the phase material, and enthalpy at a reference temperature, respectively. Furthermore, the fluid fraction of PCM is

$$f = \begin{cases} 0, T < T_{solidus} \\ \dfrac{T - T_S}{T_S - T_l}, T_{solidus} < T < T_{fluidus} \\ 1, T_{fluidus} < T \end{cases} \tag{6}$$

5.3.2. *Mathematical modeling of BTMS*

There is no doubt that BTMS controls the temperature of batteries to ensure work effectively and safely. Low temperatures may reduce battery capacity, efficiency, and charging/discharging performance, while high temperatures can speed up battery aging and pose safety issues. By removing excess heat or adding heat, when necessary, a battery's thermal management system maintains an optimal operating temperature. To control the temperature of the batteries, engineers use active, passive, or hybrid heat transfer technologies. The working fluid, which may be air, water, or another liquid, is pushed by a fan or pump in active solutions to either lower or raise the battery temperature. For heat removal from the battery, passive solutions use either heat sinks or pipelines made of thermally conductive materials. A hybrid approach combines the best of active and passive systems in a single comprehensive design. Systematic and in-depth research can be carried out in terms of numerical simulation and experiments to comprehensively reveal its performance characteristics, working mechanism, and applicable conditions [8,119]. The working principle of the BTMS is based on the key core factor of phase transition characteristics of nano-enhanced PCMs, and the working fluid (airflow) in the heat transfer medium is the main flow regime of the battery thermal management system. The governing equations coming from the Navier-Stokes model are continuity, momentum and energy equations of airflow and characteristics equations of PCMs. By establishing the mathematical model of BTMS, the 3D-CFD flow field model is used to analyze key geometric parameters of Li-battery thermal management system equipped with PCMs together with metallic fins and airflow as the working fluid.

5.3.3. *Mathematical modeling of Li-battery*

Energy conservation equation (7) for Li-batteries is [119]:

$$\rho_b C_{p,b} \frac{\partial}{\partial t}(T_b) = \dot{q}_{\mathrm{gen}} + \nabla \cdot (k_b \nabla T_b) \tag{7}$$

where ρ represents the density, C_p specific heat, k thermal conductivity, T temperature and q volumetric rate of heat generation. The subscript b stands for battery. Furthermore, q is a third-order polynomial given below in equation (8):

$$q_{gen} = a_3 t^3 + a_2 t^2 + a_1 t + a_0 \tag{8}$$

Table 3
Thermophysical characteristics for simple and nano-enhanced PCM (Paraffin for example) [133,134].

Materials	Pure Paraffin wax	+1 % nano-enhancement	+2 % nano-enhancement
Solidification T ($^\circ C$)	58.84	≈- 0.32	≈- 1.02
Melting T ($^\circ C$)	60.45	≈- 0.88	≈- 1.31
Thermal Conductivity $k(W/m^\circ C)$	0.172	≈ + 0.024	≈ + 0.054
Density $\rho(kg/m^3)$	908.6	≈ + 13.4	≈ + 23.4
Specific Heat $C_p(J/kgK)$	2981	≈- 57	≈- 117
Latent Heat (kJ/kg)	166.7	≈- 6.4	≈- 5.5

Table 4
Thermo-physical properties of different PCMs [120]).

Materials	Mass fraction of added particles	Latent Heat Unit: $kJkg^{-1}$	Thermal Conductivity Unit: $Wm^{-1}K^{-1}$	Melting temperature Unit: C	Specific Heat capacity Unit: $kJkg^{-1}K^{-1}$	Reference
GR/CNT/PW	0.5/0.6/0.7/0.8	203.8	0.61/0.81/0.87/ 0.84	40.8	–	[135]
EG/GR/CNT/ PW	–	178.5	9	46.1	–	[136]
PW		222.7	0.4	40.9	3.22	[135]
PW		224.8	0.8	46.6		[136]
PW	20	200–250	0.25	70	1.3–3.3	[120, 137]
PW		239.6	0.35	41–44		[138]
PW		198	0.38	38–48		[120, 137]
PW		143	0.19	38–81	2.3 (s)	[139]
GR/CNT/PW	0.5/0.6/0.7/0.8		0.61/0.81/0.87/ 0.84			[120, 137]
GR_1/PW	0.5/1		10/15		1.3–4.5	[120, 137]
GR_2/PW	20		37.5–52.5			[120, 137]
GR_3/PW	20		40–50		1.9–5.5	[120, 137]
GR/PW	3/5/7	235.6/226.6/ 221.5	0.75/0.95/1.2			[138]
GR/NF/PW	0.5	99	4.6		1.6 (s), 1.8 (l)	[139]

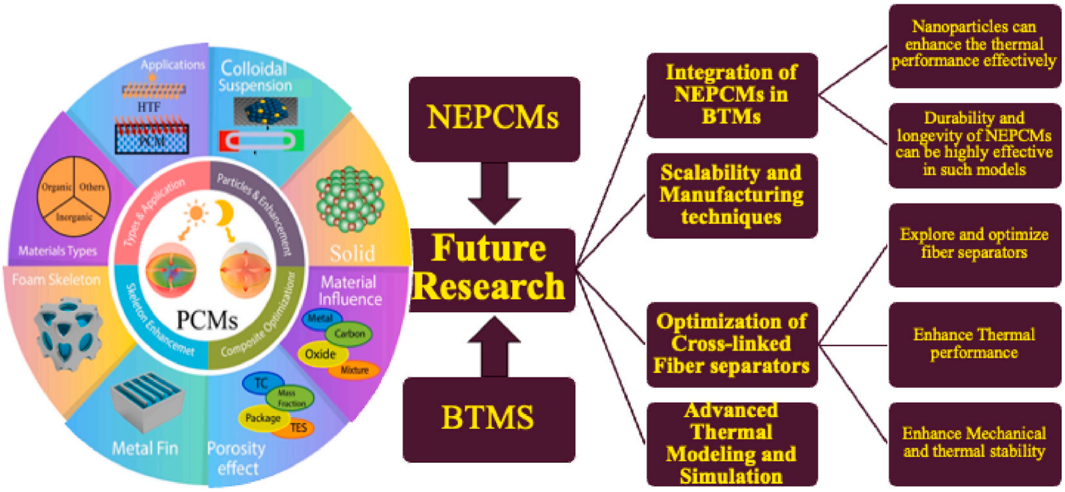


Fig. 17. Cross-linked future directions for PCMs.

such that, $a_3 = 2.07 \times 10^{-7}, a_2 = -1.62 \times 10^{-4}, a_1 = 4.19 \times 10^{-2}, a_0 = 4.28$.

5.3.4. Study for output characteristics and thermophysical properties of PCM materials

To protect the PCM, a metal casing is used. The metallic fins are fastened to the battery casing, and they extend into the PCM as well as out into the air. As a result, a portion of each metallic fin is cooled by the PCM, while the remaining portion is cooled by the airflow. Because of its lower cost and lower weight, aluminum is favored over copper for use in the construction of the casing and the metallic fins of the PCM. It is expected that discharged batteries will emit heat, which will then be transferred to the PCM in the form of perceptible heat. Tables 3 and 4 illustrate the HNF's thermo-physical characteristics for the audience' perusal.

6. Conclusions

BTMS enriched with enhanced materials such as NEPCMs result in the best performance to increase the lifetime and working capacity to demise the temperature of Li-batteries. Researchers have paid a lot of attention to the usage of nano-enhanced PCMs in BTMS because of their high efficiency and practicality. PCMs made from porous materials exhibit superior properties, including the ability to increase thermal conductivity without sacrificing their phase change temperature or latent heat. Thus, achieves the supreme ability to effectively control the maximum temperature difference of the battery module while keeping it within safe parameters. Some key findings are listed below.

(1) Using PCM and nano-enhanced PCM combined for BTMS is presented as a cost-effective approach. The investigation may be expanded to cover varied arrangements of modules, the thickness of the coating material, the kind of nano-particle and phase-change material, and different discharge rates.
(2) For efficient cooling of battery modules and improved BTMS, a liquid cooling system is preferred through nano-enhanced PCM.
(3) In recent times, there has been an excessive use of porous carbon and metal materials for Li-ion battery thermal management systems (BTMS). The use of porous-material-based enhanced (composite) phase change materials (EPCM) in lithium-ion batteries has been extensively adopted. However, enhancing their thermal conductivity and addressing the issue of phase change material (PCM) leakage have yet remained challenging.
(4) The performance of PCMs composed of porous materials is significantly influenced by the presence of porous carriers. Certain characteristics contribute to the suitability of a porous material, namely: (i) a significant level of porosity, pore surface area, and pore volume; (ii) a sufficiently sized average pore diameter; (iii) strong compatibility with the phase change material (PCM); (iv) a low level of density; (v) a high degree of thermal conductivity; and (vi) non-toxic and non-flammable properties.

7. Future directions

The next areas of investigation for enhanced (composite) phase change materials (EPCM) used in li-ion battery thermal management systems (BTMS) are as follows: (i) investigating various porous carriers, such as MOF and epoxy resin, that have the potential to be used as carriers for heat transfer applications; (ii) examining different techniques to enhance heat transfer, such as utilizing composite carriers; improving the compatibility between phase change materials (PCM) and the porous carrier to minimize thermal contact resistance; and enhancing convective heat transfer within the composite materials. Based on the literature review and discussion throughout this manuscript, key future research directions for Battery Thermal Management Systems (BTMS), nano-enhanced Phase Change Materials (PCMs), and their connection with cross-linked fiber separators are given in the following diagram (Fig. 17).

CRediT authorship contribution statement

Ghulam Rasool: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wang Xinhua:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization. **Tao Sun:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Tasawar Hayat:** Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis, Data curation, Conceptualization. **Mikhail Sheremet:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Azim Uddin:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Hasan Shahzad:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Conceptualization. **Kamil Abbas:** Writing – review & editing, Writing – original draft, Software, Formal analysis. **Izzat Razzaq:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Wang Yuexin:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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