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Review

A Review on Composite Phase Change Materials and Fins-Based Li-Ion Battery Thermal Management Systems with Design Perspectives and Future Outlooks

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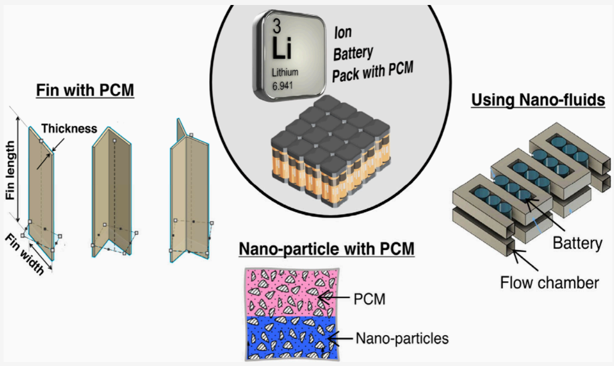
ABSTRACT: Electric vehicles (EVs) are frequently powered by Li-ion batteries (LIBs) due to their substantial capacity of energy; nevertheless, thermal runaways (TRs) can cause performance issues and safety dangers. Battery thermal management systems (BTMs) are essential for mitigating the difficulties by lowering the extreme temperature of the battery and the differential temperature. Among the several BTMS technologies, phase change material (PCM) embedded systems have received a lot of interest, because of their simplicity, low cost, and elevated latent and sensible heat. The current study analyzes the passive BTMS (mostly on PCM and fin-based) for cylindrical LIB, looking at the impact of temperature on the battery performance. The invesigation has focused on the performance of battery cooling, in conjunction with PCM, and the enhancement of thermal conductivity through the use of metal foams, nanometal oxides, and carbon particles. A systematic review focusing on innovative fin configurations is also presented to evaluate the effects of different fin characteristics on the efficacy of BTMS. Moreover, to make the studies more practical in application, lightweight PCM-BTMS, structural stability, space availability, and innovative fin shapes, such as spiral fins, with optimal placement concepts are discussed. The constraints of batteries, PCMS, and thermoelectric coolers are investigated further in order to foster viable solutions for BTMS for EV applications. The goal of this assessment is to provide guidance for the development of practical BTMS that meet power, volume, and weight requirements.



1. INTRODUCTION

Due to the tremendous population expansion, the need for energy is increasing every day throughout the world. The conventional automotive sector is one of major contributors to the greenhouse emissions.[1] As a result, policymakers are increasingly favoring electric vehicles (EVs) as the most promising transportation technology, which is more environmentally friendly than internal combustion-driven vehicles.[2,3] A survey of global EV demand between 2020 and 2030 is reported in Figure 1.[4] Arguably the most intriguing innovations for utility-scale electricity storage and transmission are batteries for EVs. In this context, Li-ion batteries (LIBs) are extensively used to power the EV, due to their high power and energy densities.[5−7] Over the past several years, there has been a significant increase in incidents involving fires and explosions in LIB.[8−10] The high flammability of the electrolyte in the LIB poses a major fire hazard during its usage if there are any faults in the design or production process.[11] Therefore, ensuring the thermal safety of these batteries has become a crucial factor limiting their widespread use. Due to its great efficiency, hybrid battery thermal management systems (BTMS) have drawn increasing interest. However, many factors significantly affect how much energy is used and how well the combined BTMS performs, making it necessary to suggest a practical cooling

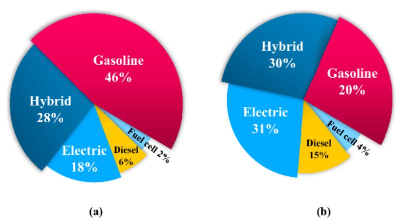


Figure 1. A prospective study on obliged for electric vehicles worldwide between (a) 2020 and (b) 2030.

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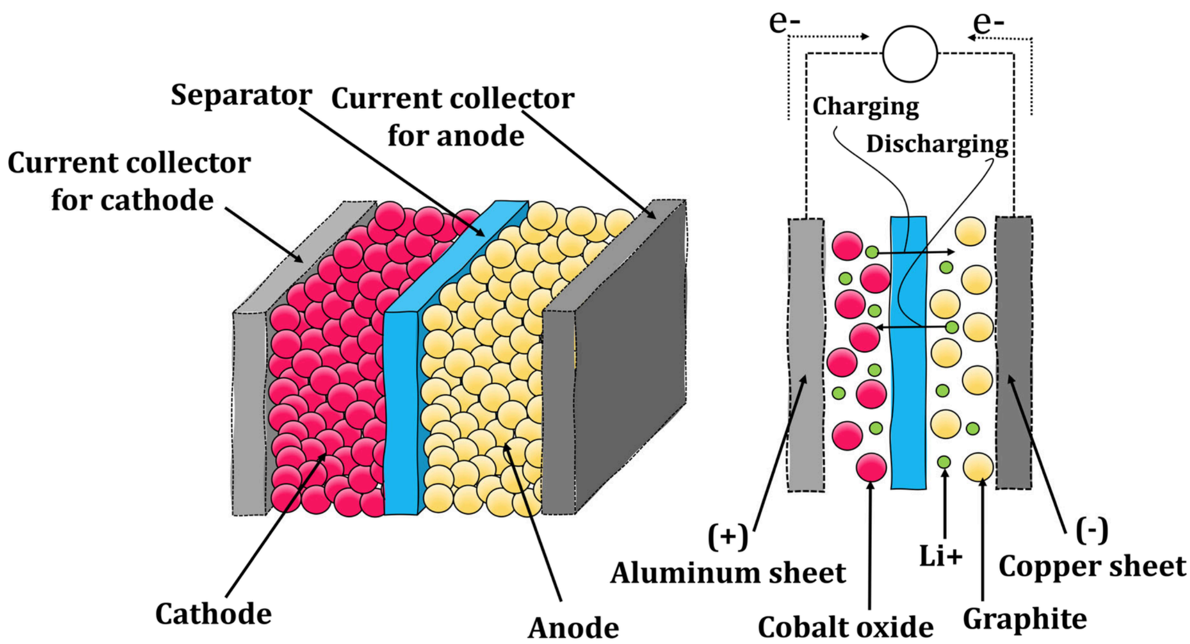

Figure 2. Constructional details of a lithium-ion battery (LIB) cell and its mechanism.

Table 1. Different Types of LIBs and Their Properties

battery type	Electrode Material: cathode	Electrode Material: anode	operating voltage (V)	operating temperature (°C)	specific capacity (mAh/g)	thermal runaway (°C)	ref
lithium−cobalt oxide	$LiCoO_2$	graphite	3.6−4.2	−20−55	140−180	150	24
lithium−nickel manganese cobalt oxide	$LiNiMnCoO_2$	graphite	3.7−4.2	–	140−180	210	24
lithium iron phosphate	$LiFePO_4$	graphite	13.2−13.6	−30−60	160−180	270	24
lithium−manganese oxide	$LiMn_2O_4$	graphite	2.8−3.2	−40−60	90−130	250	25
lithium titanate	$LiMn_2O_4$	$Li_4Ti_5O_{12}$	1.9−2.5	−40−60	170−180	177	26

technique and an intelligent technique to optimize different parameters with minimal computing load.[12−16]

Figure 2 presents the constructional details of a LIB cell and its mechanism. Li^+ ions cross the separator from the cathode region to the anode area during the discharging process, and the process is reversed during the charging state. Redox reaction occurs during the charge transfer process at the electrode, producing additional electrons whose flow through an external circuit results in electricity. Within this spectrum, there are multiple varieties of LIBs. such as lithium nickel cobalt manganese oxide ($LiNiCoMnO_2$), lithium iron phosphate ($LiFePO_4$), lithium nickel manganese spinel ($LiNi_{0.5}Mn_{1.5}O_4$), lithium nickel cobalt aluminum Oxide ($LiNiCoAlO_2$), lithium manganese oxide ($LiMn_2O_4$) and lithium cobalt oxide ($LiCoO_2$), including module, polymer, prismatic, and battery pack formats. Equation 1 depicts a reaction that occurred at the cathode ($LiFePO_4$) while eq 2 depicts a redox reaction that occurred at the anode (carbon).[17]

$$nLi^+ + Fe^{3+}PO_4 + (1-n)LiFe^{2+}PO_4 + ne^- \rightarrow LiFe^{2+}PO_4 \quad (1)$$

$$Li_nC_6 \rightarrow nLi^+ + C_6 + ne^- \quad (2)$$

To analyze and implement techniques and technological advances for substantially managing the variety of temperatures of the battery cells and consequently enhancing their functioning, much research on BTMS has been conducted.[18,19] The BTMS is essential since the resilience of the battery cells is directly impacted by temperature, power availability, and drivability.[20] In BTMS, PCM, liquid and air cooling are typically used. Due to their simplicity of use and low cost, liquid and air-cooling strategies are widely used.[1,21−23] The properties of different types of LIBs are reported in Table 1.

This study delves into the various design and operating approaches of several BTMS types, including air and liquid-oriented BTMS, and heat pipe-oriented BTMS. The present paper offers a summary of the latest advancements in PCM-based methods for maximizing thermal conductivity, including expanded graphite and fibers, metal mesh, metal fibers, and metal foam. To the best of the authors' knowledge, there are limited works available that go through a detailed analysis about the variety of materials that can be incorporated with PCM and how the perform with PCMs, the fin number in the PCM module, impact of the external heat-transfer coefficient on the PCM module and provides some innovative ideas and biomimetic approaches in this field. Moreover, to make the studies more practical in application, lightweight PCM-BTMS, structural stability, space availability, and innovative fin shapes, such as spiral fins, with optimal placement concepts are discussed. The paper describes the challenges and potential outcomes of using BTMS to develop LIB technology.

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Table 2. Summary of Literature Related to Investigating the Temperature Effects on the Battery

battery type	test method	temperature range	key findings	ref(s)
lithium-ion	experimental	−20 °C to 60 °C	The storage capacity increases by 20% from 25 to 45 °C at higher temperatures but reduces the battery's lifespan. Charging at 45 °C can result in greater deterioration than charging at 25 °C.	27, 28
sodium-ion	simulation	−70 °C to 100 °C	At −70 °C, this power source generates 70.19% of its stored energy at the ambient temperature. This battery also performs effectively at 100 °C due to the electrolyte's high boiling point.	29
lead-acid	simulation	−10 °C to 25 °C	Discharge rates lower battery capacity and vice versa. Temperature boosts battery capacity. At 30 °C, battery capacities for 2, 3, and 4 Ω are 57.783, 58.74, and 60.467 Wh. At 2 Ω, battery capacities at 30, 40, and 50 °C are 57.783, 58.175, and 58.213 Wh. Temperature accelerates the voltage decrease.	28

2. TEMPERATURE EFFECT ON LIB PERFORMANCE

Although the battery may store heat, the main issue is that when it is being discharged, the battery's internal temperature increases. Temperature extremes have a significant detrimental impact on batteries, shortening their life cycles and posing safety risks. Thermal runaaway (TR) can occasionally be caused by extreme overheating. Table 2 lists various studies looking into how batteries are affected by temperature.

2.1. The Process of Thermal Runaway and Methods of Prediction. The generation of heat due to the exothermic reaction inside the battery causes the TR. The battery cell temperature rises due to the accumulation of the generated heat, which leads to an exponential increase in the exothermic reaction rate. At cell temperatures over 80 °C, the exothermic process becomes uncontrollable, leading to a constant increase in the temperature of the battery pack and finally resulting in TR.[30,31] Furthermore, the internal component of the battery cell starts to decompose when the battery temperature reaches 130−150 °C.[32] For example, the electrolyte begins to break down at temperatures between 100 °C and 120 °C. The diaphragm, which is made of polyethylene (PE) and polypropylene (PP), is damaged at ∼135 °C. The solid electrolyte interlayer (SEI) on the solid anode electrode starts to dissolve at roughly 80 °C. The decomposition of the electrolyte leads to the production of enormous quantity of flammable gases, particularly H_2, CH_4, C_2H_6, and C_2H_4, which can further cause fire in the battery cell at higher temperature.[33] In addition, the battery will immediately release huge amount of heat stored in the electrical energy and gas production due to the damage of separator and being the short circuit phenomena inside the battery cell. This phenomenon of releasing heat exacerbates the abnormal temperature rise and the chain reaction occurs until TR happens.

There are mainly three steps in a TR. Due to separator faults, the battery experiences a change in condition in the first stage that causes an increase in internal temperature and eventually, the start of overheating. The battery experiences an exothermic reaction in the second phase, as a result of a sharp increase in internal temperature.[13] In the third phase, flammable electrolytes burn and cause an explosion. Additionally, high temperatures are caused by the heat that builds up inside batteries during charge−discharge cycles, which shortens their lifespan and affects their functionality. Figure 3 illustrates a diagram of the TR.

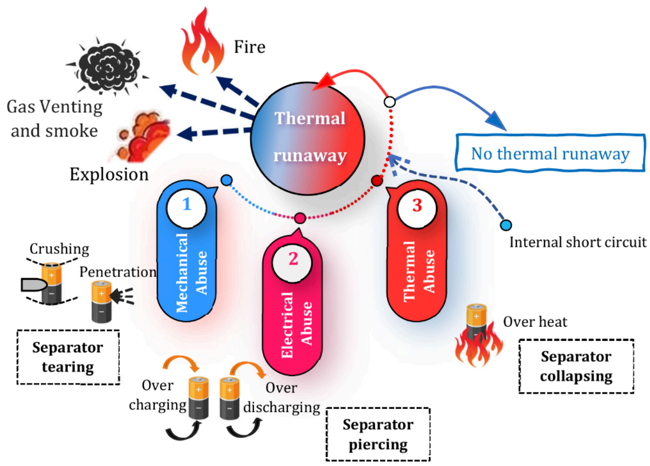

Figure 3. Effect of temperature change inside the LIB cell.

The prediction and warning methods for the TR in LIBs are developed using the battery's electrochemical mechanism and data.[34] The battery heat generation and the TR boundary are estimated on the basis of the coupled electrochemical−thermal model and the battery operating conditions, respectively, in terms of the TR prediction and early warning methods on the basis of the electrochemical mechanism of the cell. In addition, the TR of the battery cells and battery packs can be measured by monitoring the concentration of gas, particularly CO_2, CO, etc. at the early stage of the TR. A study shows that more flammable gases will be released in LIBs during the overcharging state, resulting in a greater explosion which can be the indication of TR condition of the battery.[35] The characteristic of the electrochemical impedance spectrum can be the sign of warning of TR in LIBs, which will help to estimate the real-time temperature inside the battery cell and detect battery overcharging through the characteristic spectrum. To develop an accurate and widely applicable method for predicting and warning about TR in lithium-ion batteries, a multiscale approach should be constructed. This approach should consider both external factors such as temperature, voltage, and current, as well as internal mechanisms like electrochemical reactions and material changes.[34]

2.2. Thermal Management System of Batteries. Heat generation in LIBs is due to both reversible and irreversible processes. The reversible process is caused by the entropy change during the electrochemical reaction and the irreversible process, including the ohmic heat generation, a heat production due to the polarization process, and the transportation of ions through the electrolyte.[36−38] The polarization process in the battery cell leads to the accumulation of hydrogen bubbles in the surface of the anode and resists the normal flow of ions. When the lithium ion exceeds this resistance, heat is generated.[39] Furthermore, the huge amount of heat emission also occurs for the disturbance of ion transportation and the mixing of ions due to the overcharging and rapid discharging process.[40] The enormous amount of heat generation enhances the battery internal temperature and, if the temperature goes beyond 80 °C, exothermic reactions become uncontrolled, leading to TR. Temperatures above 40 °C have a detrimental effect on the functionality and service life. During the ideal conditions of 15−40 °C, LIBs function

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effectively.[41−43] A schematic diagram of battery performance at different temperature ranges of LIB is presented in Figure 4.

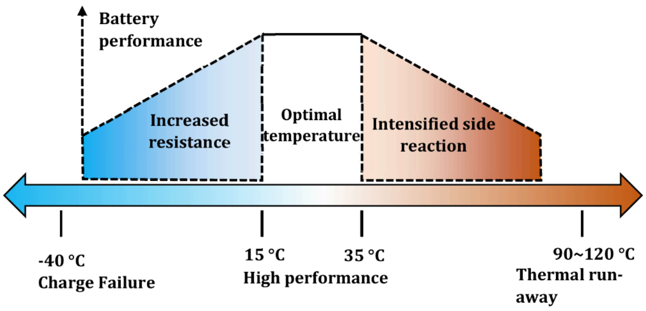

Figure 4. Temperature range of the LIB.

When the temperature difference between the cells exceeds 5 °C, 2% reduction of the battery capacity takes place.[44] Therefore, it is necessary to maintain the battery's state and the lowest temperature disparity between the battery pack inside the limits set forth of 15−35 °C.[13] Hence, BTMS is regarded as the effective way to extract the generated heat from the battery cell and reduces the changes of overheating or TR, therefore improving the performance of the battery. In the recent year, many strategies related to BTMS have been proposed and adopted in the research community to control the temperature of LIBs.[45] Figure 5 depicts the different types

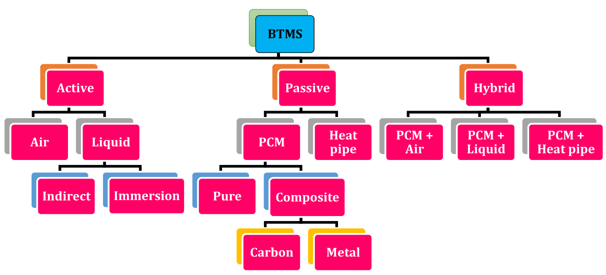

Figure 5. Studies to related different BTMS.

of BTMS applied in the battery for cooling purposes. BTMS technology can be classified as main three types, based on the medium used, viz, air-based, liquid-based, and PCM-based.[46] At present, active liquid cooling, active air cooling, heat pipe, PCM, PCM with thermal conductivity enhancer additives, and fin-based BTMS cooling technology have been attracting attention in the research community. Moreover, different resources all over the world have been experimenting with different active BTMS systems and determining the results. Some resource data of air and liquid-based, thermoelectric-based, and heat pipe-associated BTMS systems are tabulated in Tables 3−6, respectively.

3. AIRE AND LIQUID-BASED THERMAL MANAGEMENT OF BATTERIES

Thermal control of batteries utilizing air as a cooling medium is known as "air-based battery thermal management". Electric automobiles and other applications where liquid cooling systems would not be practicable frequently employ this technique. In order to maintain the required temperature range, air-based BTMS often use fans to supply air over the battery pack. To increase the degree of cooling even more, air may occasionally be precooled before being supplied with the battery pack.

One of the advantages of air-based BTMS is its simplicity, less weight, and lower cost in contrast to liquid-based cooling systems. Additionally, air-based systems are less prone to leaks and other maintenance issues that can arise with liquid cooling systems. However, air-based BTMS may not be as effective as liquid-based systems in some situations. For example, in extremely high-temperature environments or when the battery is operating at high power levels, an air-based system may not be able to maintain an adequate range of temperature. A lot of resources have been done on air-based BTMS. A schematic air-based BTMS is shown in Figure 6. and research findings are tabulated in Table 3.

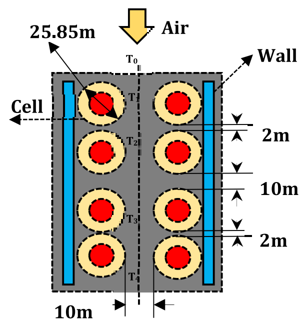

Figure 6. Air-cooled packs of batteries board arrangement showing thermal couplings and cell arrangement. [Reproduced with permission from ref 47. Copyright 2014, Elsevier.]

It is demonstrated that, despite advancements and optimizations, air cooling is insufficient when the battery discharge rate is higher and operating at high atmospheric temperatures.[42] Because coolants have a higher specific heat capacity than other materials, researchers have suggested cooling circuits that use water, acetone, oil, or glycol. However, the effectiveness of liquid cooling comes with additional expenses, complexity, size, and leakage problems. These problems need to be fixed if a BTMS uses liquid cooling. Figure 7 depicts the liquid-based cooling systems.

Heat pipes (HP) have proliferated in temperature control applications recently, including the cooling of electrical equipment and spacecraft. It has become a potential substitute for battery temperature control due to minimal servicing costs, versatile layout, and better heat-transfer capacity than solid conducting material.[21,57−59] Figure 8 shows a schematic of a HP-based BTMS. Table 4 shows different heat-transfer fluids, which have been used in indirect−contact mode by many researchers to investigate their efficacy on the BTMS.

The design and implementation of air-based systems can be done reasonably easily and affordably. Usually, they demand simpler engineering and fewer components. However, air is less thermally conductive and has a lower heat capacity than liquids, which makes air-based systems less effective in removing heat. Liquid-based solutions are more successful at removing heat from batteries, because liquids have a higher heat capacity and thermal conductivity than air. By distributing the battery pack's temperature more evenly, liquid cooling can lessen stress and thermal gradients. Conversely, the design and maintenance of liquid-based systems are more costly and complex. Pumps, tubing, heat exchangers, and coolant fluids are needed for them. Heat pipes do not require external pumps

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Table 3. Experimental Findings of Air-Based BTMS

type of the battery	modification	remarks	ref
cylindrical	airflow velocity and configuration of cells	variation in flow rates, varied section configurations, and distance between cell and wall were carried out.	47
cylindrical	cell arrangement	for temperature change, a large battery pack having adequate distancing.	48
cylindrical	flow path/ cell arrangement	effects of plenum plate angle and battery unit spacing	49
cylindrical	flow path/ cell arrangement	the pattern is round, hexagonal, and rectangular, and there are fans at various points.	50
cylindrical	cell arrangement	in a manner of aligned and staggered arrays	51
cylindrical	flow path	improving temperature homogeneity by using reciprocating air flow	52
cylindrical	flow path	cell arrangement with alignment and staggering	53
cylindrical	flow path	combine reciprocating cooling flow with hysteresis	54
cylindrical	air flow rate/cell arrangement/ flow path	effects of air inlet velocity, staggered cell configuration, and periodic air flow reversal	55
cylindrical	flow path	for cooling, splitter plates with flow guide-vanes	56

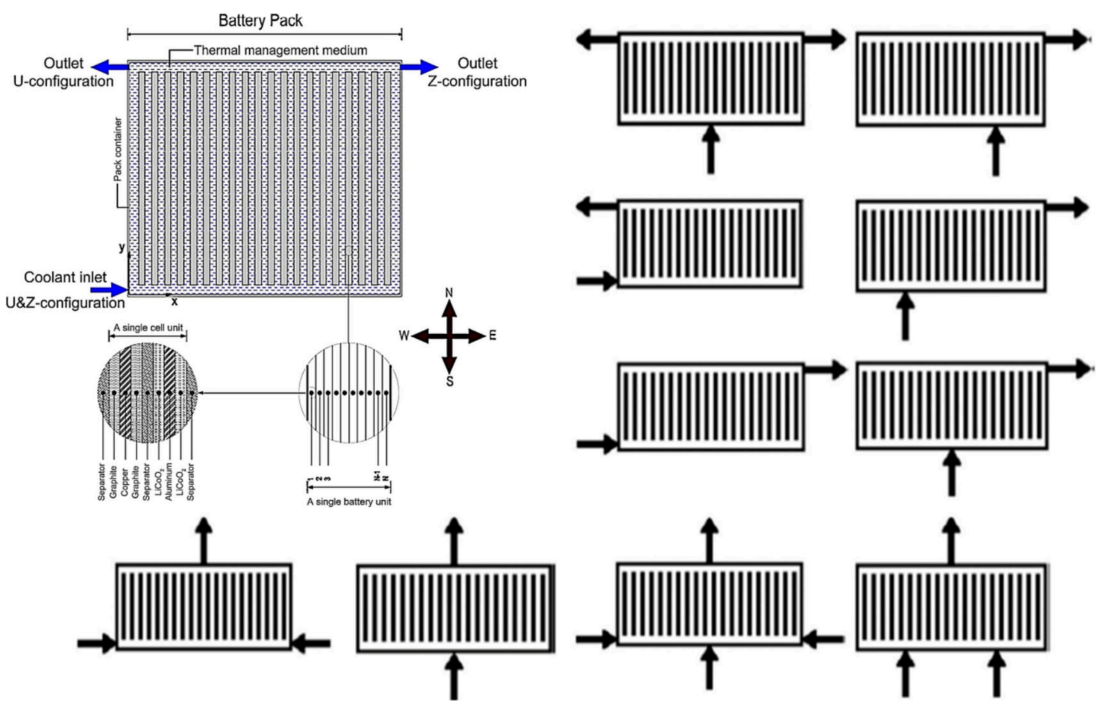

Figure 7. Liquid-based BTMS with different configurations. [Reproduced with permission from ref 80. Copyright 2014, John Wiley and Sons.

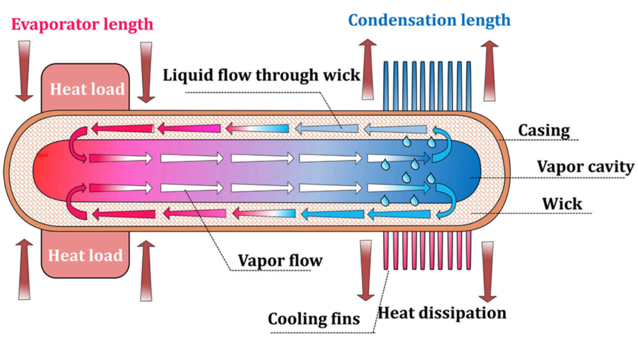

Figure 8. Schematic and working principle of the heat pipe.

or fans to function passively, which lowers energy usage and potential failure points. They transport heat effectively and with little temperature differential, thanks to their strong thermal conductivity. For efficient heat transfer and thermal contact, heat pipes must be carefully designed into battery packs. Quality heat pipes can be more costly, which could raise the BTMS's total cost.

4. PASSIVE THERMAL MANAGEMENT WITH PCM

The temperature of the LIB can be managed passively through the use of PCM. This strategy involves integrating a material that absorbs and emits heat on phase change as a thermal shield between the battery and its surroundings. When the system temperature rises over a certain point, the PCM melts, absorbing the heat and maintaining a constant temperature. The heat is then released when the battery temperature falls. LIB with PCM for heat management has increased energy density, longer cycle lives, and improved safety. The drawbacks associated with PCM are its limited operating temperature range and the complexity of the battery's construction using PCM.[81] The PCM material and design that is selected can have an impact on the thermal management capabilities of LIBs. The conductivity of heat, its limit, encapsulation technique, and positioning of the PCM within the battery store can all affect how well the battery performs. Table 5 displays some of the thermochemical characteristics of PCM.

Recent advancements in PCM technology for thermal control have centered on enhancing the PCM's performance

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Table 4. Different Heat Transfer Fluids That Have Been Used in Indirect-Contact Mode

heat-transfer fluid	effectiveness and limitations	ref(s)
water	Water is affordable for large-scale thermal management systems, since it is easily available and inexpensive. Water, however, can lead to scale and corrosion in cooling systems. Furthermore, dissolved ions or other impurities may cause it to become electrically conductive, which could be dangerous in particular applications.	21, 60−67
deionized water with $(C_3H_3NaO_2)_n$	Due to its far lower electrical conductivity than ordinary water, deionized water lowers the possibility of electrical problems or short circuits in the event of a leak. Despite being an organic polymer, polyacrylate does not affect the conductivity of deionized water. Considering the polyacrylate solution's stability over time is necessary since any precipitation or deterioration may reduce the efficiency of the heat-transfer fluid	68
ethylene glycol $(C_2H_6O_2)$/water	Use of the water mixture in colder climates is safe because ethylene glycol drastically decreases the freezing point of the liquid. Maintaining battery performance under varied environmental conditions is especially dependent on this. However, compared to pure water, ethylene glycol makes the mixture more viscous. Increased viscosity may have an effect on the system's overall efficiency by lowering flow rate and raising the pumping power needed to circulate the fluid.	69−73
mineral oil	Mineral oil functions exceptionally well as an electrical insulator. This is a major advantage over fluids based on water, since it lowers the possibility of short circuits in the event of leaks. The thermal conductivity of mineral oil is lower than that of water and combinations of ethylene glycol and water. It is therefore less effective in removing heat from the battery cells.	74
Al_2O_3/water nanofluid	The thermal conductivity of water is considerably increased by AlO_3 nanoparticles. This improvement raises the effectiveness of heat transfer, which makes it possible to cool the battery cells more successfully. If the suspension is not adequately stabilized, the nanoparticles may eventually settle out, resulting in erratic thermal characteristics and even cooling system obstructions. It is essential to provide steady dispersion of nanoparticles.	75, 76
liquid metal (gallium, Ga^{80} In^{20}, Ga^{68} In^{20} Sn^{12})	Large volumes of heat may be absorbed and transferred by liquid metals, which lowers the risk of overheating and thermal runaway by assisting in the maintenance of steady temperatures inside the battery pack. On the other hand, liquid metals can be costly, particularly those that contain tin or indium. The cost of the thermal management system as a whole may increase, due to the price of these materials and the requirement for specialist handling and containment.	77
Novec 7000	The nonflammability of Novec 7000 (fluorinated ketone) lowers the risk of fire, which is an important safety factor in battery management systems. Because Novec 7000 has a lower specific heat capacity than water, it absorbs less heat for a given rise in temperature. This may be utilized for higher flow rates or a more sophisticated cooling system.	78
R134a	Because of its advantageous thermodynamic characteristics, R134a (1,1,1,2-tetrafluoroethane) can transport heat effectively during phase changes, such as evaporation and condensation, because of its high latent heat of vaporization. Weak containment measures are required because R134a, being a refrigerant, can leak out of tiny spaces. Environmental effects and a decline in performance are further consequences of leakage.	79

Table 5. Thermochemical Properties of Several PCMs

PCM	latent heat of fusion (kJ/kg)	melting point (°C)	density (kg/m^3)	thermal conductivity (W (m K)$^{-1}$)	ref
paraffin wax	150−250	42−56	880−950	0.20	87
beeswax	177	61.8	950	–	88
erythritol	340	117	1450	0.73	89, 90
octadecane	243−244	27.5−28	774	0.15−0.36	88
palmitic acid	222	61	989	0.21	87
stearic acid	160	55.1	848−965	0.172	91
lauric acid	177.4−211.6	41−44.2	848−1007	0.139−0.192	88
acetic acid	192	17	1214	0.26	87
urea	250	134	1320	0.22	92
acetamide	241	81	1159	–	88

and longevity, such as through the use of microencapsulation or the incorporation of nanomaterials. For instance, the usage of microencapsulation and nanomaterials enhance the thermal conductivity and charging/discharging rate of the PCM.[82,83] The melting process of Cu/paraffin nano-PCM was examined both experimentally and numerically by Shuying et al.[84] The results demonstrated that the addition of 1 wt % of Cu into the PCM reduced the melting time of pure PCM by 13.1%. These methods have yielded promising results, exhibiting enhanced thermal and cyclic stability. The design and manufacture of the battery store, the choice of PCM material, the placement of PCM inside the pack, and the compatibility of the PCM with other battery components are all practical concerns for adopting passive thermal management using PCM in real-world applications. Opportunities and challenges for enhancing the thermal management performance of LIBs using passive PCM-based approaches including optimizing the PCM properties and design, developing more efficient and cost-effective manufacturing methods, and integrating advanced sensing and control systems to ensure effective thermal management are still ongoing development processes. There are numerous PCMs for heat management, including paraffin, fatty acids, and salts.[85,86] Many researchers have been doing investigations on battery thermal management for various batteries and PCM applying different methodologies. Some of the findings are tabulated in Table 6.

4.1. Pure PCM-Based BTMS. PCMs are the only materials used in pure PCM-based BTMS that serve as the heat sink for dissipating heat produced by LIBs during charging or discharging cycles. PCMs effectively maintain the battery's target temperature by absorbing extra heat during the progression of solid−liquid phase change and storing it as latent heat. With the battery cells, the PCM which maintains close contact with pure PCM-based BTMS, enabling effective and efficient heat transfer. The benefit of using a PCM in the BTMS is that it reduces the temperature swings of the battery, hence extending its life and improving performance. PCM implementation within BTMS was recommended by Al-Hallaj and Selman[100] and reported a more-consistent temperature distribution than the natural and induced convective BTMS. A test prototype was built and discovered that the battery peak temperature decreased at a discharge rate of 1 C. Duan and Naterer[94] conducted exploratory evaluations of two distinct PCM-based battery cell management systems designs: the PCM attire surrounding the battery pack and the overall PCM

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Table 6. Review of Studies Related to BTMS Using Different PCMs

PCM type	battery type	methodology	performance metrics	operating conditions	key findings	ref
paraffin wax	battery pack (cylindrical batteries)	simulation	discharge rate, depths of discharge (DOD), temperature increase	discharge rate = C/1−C/6, DOD = 0.25−1.0, axial distance = 0.1−3.76 cm	when a battery module with PCM was used instead of a 100 Ah cell with same cooling settings, the temperature rise was considerably lower. The temperature difference between the surface and center of 100 Ah cells is substantial at high cooling rates.	93
PCM flexible sheets[a]	cylindrical battery cell	experimental	temperature, heating rate	voltage supply of heater = 1.5−12 V, each process withstands 5 min. Temperature increase = 50 °C	With a 7 °C decrease in the steady-state heater surface temperature, the PCM jacket has a good cooling effect.	94
paraffin	cylindrical battery	numerical analysis	heating power, temperature, liquid fraction	heating power = 6.6−13.2 W, time = 200−2200 s	PCM shows an observation similar to the metal housing case when the acrylic housing is used, although it melts more quickly.	95
solid−liquid phase change composite[b]	electric bike battery pack (10s4p configuration)	experimental study	propagation sequence for different packs, temperature with and without PCC	voltage (0−4 V), temperature (20−225 °C)	after toenail penetration, the application of PCM reduced the temperature of adjacent cells by 60 °C and stopped thermal escape transmission throughout the cells.	96
beeswax	rectangular battery	simulation	heater power, temperature of battery, and beeswax	the battery operates between 25 and 55 °C, with a heater power of 40−60 W	Heat pipes containing beeswax or RT 44 HC can reduce the surface temperature of the battery by 31.9 or 33.2 °C, respectively.	97
octadecane, $C_{18}H_{38}$	rectangular battery	numerical simulation	TMS thickness, heat flux, discharge time	heat flux = 400−800 W/m^2, thicknesses of TMS = 7.5−15 mm	adding metal matrix to octadecane improved battery performance by increasing discharge time and decreasing surface temperature	98
					battery-generated heat loss is more effectively stored by gallium and octadecane−Al foam thermal management systems (TMSs), compared to pure octadecane TMSs	
polyethylene glycol 1000, $H-(O-CH_2-CH_2)_n-OH$	cylindrical battery pack	mathematical modeling	charging−discharging rate, temperature	discharge rate = 1−4 C	surface temperature was lowered, and battery performance was increased by using PCM and mesh plates of aluminum wire between battery cells, with a reduction of maximum cell surface temperatures by 19%−26% for different charging rates	99

[a]T-PCM 920, manufactured by Laird Technologies. [b]Graphite matrix.

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Table 7. Thermal Properties of PCM after Adding Additives

PCM type	thermal conductivity of PCM (W (m K)$^{-1}$)	additives	thermal conductivity of the mixture	country	ref
paraffin	0.25	graphene	45	USA	103
1-tetradecanol	0.33	silver nanowire	1.47	Hungary	104
N-docosane	0.21	graphite powder	0.82	Turkey	105
hexadecane	0.16	Al particles	1.24	China	106
inorganic eutectic	0.48	carbon fiber	1.8	Italy	107

Table 8. Several Composites and Their Properties, along with Thermal Conductivity

CPCM	thermal conductivity of PCM (W (m K)$^{-1}$)	pore size (PPI)	porosity (%)	thermal conductivity of CPCM	country	ref
pure paraffin/nickel foam pure paraffin/copper foam	0.31	25	97.28	1.22	China	112
		10	97.65	0.98		
		5	97.17	1.28		
		25	96.96	4.6		
		10	96.58	5.2		
		5	96.83	4.95		
paraffin/ copper foam	0.2	20	97	0.80	China	113
			95	6.35		
			90	11.33		
paraffin/ expanded graphite	0.2	–	–	14.5	USA	114
paraffin/ expanded graphite	0.2697	–	–	4.676	China	115
PCM/aluminum foam	0.25	40	80	43.8	USA	116

canister. who discovered that both designs were successful in keeping the desired battery temperature. They also looked at how the PCM jacket performed in various heating rates and environmental conditions. In another study, Hemery et al.[101] comparison of PCM-based BTMS to forced and natural air-cooled BTMS revealed that PCM-based BTMS was more successful at achieving temperature homogeneity, with 0.5 C, as opposed to 4 C in natural convection, and 1 C in forced convection. However, it was discovered that 3 m/s forced convection outperformed PCM-based BTMS when reducing the battery temperature. A theoretical model for PCM-based cylindrical battery cooling was developed by Yang et al.[95] and experimentally validated by PCM melting around battery cells and reported that metal housing (metal and acrylic) provides a better thermal management choice, since PCM melted more slowly inside the acrylic housing, because of PCM's adherence to the acrylic housing. Yan et al.[102] constructed a composite board for battery cooling with a heat-conducting shell, an insulating panel, and PCM and found that the PCM latent heat increased from 225 kJ/kg to 2250 kJ/kg, the TR was prolonged from 451 s to 674 s. PCM has its ability to extract heat from the battery cell but it has a drawback: its low thermal conductivity. Therefore, many researchers have used many additives for enhancing the heat-extraction rate, shown in Table 7.

4.2. Composite-PCM (CPCM)-Based BTMS. Composite-PCM (CPCM)-based BTMS have gained considerable attention, because of their increased capacity for heat control in recent years, compared to conventional BTMS systems. A CPCM is created by combining two or more materials with distinct melting temperatures and latent heat, resulting in a higher temperature to melt down and conceal heat than the separate PCM components, allowing it to absorb and release heat more effectively throughout the battery's charging and discharging cycles.[108] CPCMs have many advantages over traditional PCMs, including higher thermal conductivity, better mechanical properties, and shape stability.[109,110] They are an effective thermal energy storage (TES) medium and can store higher heat per unit volume, compared to the sensible storage materials like masonry or rock.[111] Adding other material mixes with the base PCM, it improves the thermal conductivity of the base PCM, as shown in Table 8. The summary of the recent works for cooling of battery by using CPCM is given in Table 9. Hybrid and CPCM have achieved significant thermal management than pure PCM as shown in Figure 9. Some CPCMs are described as follows.

4.2.1. PCM with Carbon-Based and Other Metal Oxide Nanocomposites. An innovative strategy to increase battery thermal management is PCM with a carbon-based thermal conductivity enhancer. It has been demonstrated that adding carbon-based components to the PCM, such as graphene, carbon fibers, and carbon nanotubes, considerably improves the thermal conductivity and facilitates more effective heat transmission between the battery pack and the PCM.

According to a study by Bahiraei et al.,[127] adding graphene platelets and carbon nanofibers increase the thermal conductivity of 620% and 1100%, respectively. Results of their indicate that it is possible to optimize the development of PCM-based thermal management systems by utilizing the tradeoff between the enhancement of thermal conductivity and the suppression of natural convection inherent in nano-composites. Carbon fibers are widely used in the aerospace and automotive industries because of their stiffness, high strength, and thermal conductivity. The incorporation of carbon fibers into PCMs can significantly improve their thermal conductivity, allowing for faster charging and discharging rates. Additionally, overall properties of the PCM including mechanical properties can also be ameliorated by the addition of carbon fibers, making it more resistant to deformation and cracking during repeated phase change cycles. Babapoor et al.[128] paired PCM with carbon fibers to improve the battery's thermal performance. They used experimental methods to examine the battery's performance while adjusting the mass percentage (32%, 46%, and 67%) and the lengths of the carbon fiber (2, 3, 5, and 8 mm) at heat dissipation rates of 2 and 4 W. The outcome showed that a mass fraction of 0.46% was

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Table 9. Summary of the Recent Works for Cooling of Battery by Using CPCM

PCM type	battery type	system description	important outcomes	ref
electric-conductive paraffin/EG	18650 LIB	adding the electrically conductive CPCM to the battery to provide both warm and cool effects.	• This technology can lower the battery temperature from 77 °C to 43 °C at a discharge rate of 3 C. The battery can be kept between 20 and 55 °C. • Enhance thermal conductivity up to 960%.	117
AlN/PA/EG/epoxy resin	18650 $LiFePO_4$ battery	inclusion of different mass fraction of aluminum nitride (AlN) into CPCM for cooling purposes.	• Inclusion 20 wt% of AlN into CPCM exhibited optimum performance. • The greatest temperature drop of 19.4% and the temperature difference of < 1 °C were recorded at a discharge rate of 3 C. • Thermal conductivity improved from 1.48 W $(m\ K)^{-1}$ to 4.331 W $(m\ K)^{-1}$ at 50 °C. • Tensile strength improved by 164.2%, bending strength improved by 67.6%, and impact strength improved by 38.1%.	118
Kaolin/EG/paraffin	1965140 rectangular battery	Incorporation of the optimum composition (10 wt% EG and 10 wt% kaolin) into PCM for cooling the battery pack.	• At a discharge rate of 4 C, the temperature and the difference in temperature of single cell restrained at 45 and 5 °C, respectively. • The maximum reduction of temperature was obtained 25.77% at a discharge rate of 4 C. • Enhance thermal conductivity by 20 times.	119
Aluminum foam/paraffin RT27 composite	LIBs18650 cell	Introducing of aluminum foam into PCM for cooling the battery.	• Battery cell temperature was kept below 27 °C. • Inclusion of aluminum foam into PCM accelerated the heat dissipation rate.	120
Novel flame-retarded CPCMs/ paraffin/EG/APP/RP/ER	18,650 ternary battery	Preparation of CPCM matrix with paraffin (PA)/ EG/ APP/RP/ER and insertion of the battery into the matrix for cooling purposes.	• A temperature reduction of ~44.7% was obtained for this system. • The temperature difference maintained within 5 °C.	121
Novel form-stable and flexible CPCM	Pouch lithium battery	Creation of TPEE-SBS/EG/PA and TPEE-SBS/PA module for the insertion of battery for cooling purpose and compared the performance of both systems.	• The system TPEE-SBS/EG/PA shows better results than TPEE-SBS/ PA. • The highest temperature of TPEE-SBS/EG/PA was recorded at 66.4 °C. • Increased thermal conductivity from 0.24 W $(m\ K)^{-1}$ to 12 W $(m\ K)^{-1}$.	122
CPCM/ SAT-Urea/EG	LIB	Preparation of CPCM/ SAT-Urea/EG for thermal management of the battery.	• Inorganic PCM is safer than organic PCM to guard the battery from thermal runaway. • Thermal conductivity improves from 0.61 W $(m\ K)^{-1}$ to 4.96 W $(m\ K)^{-1}$.	123
GF-NPCM	18650 LIB	Preparation of thermal management system with novel PCM/ EG/ER along with graphite film and insertion of battery into the matrix.	• Highest temperature and temperature difference of battery pack by ~33 and 1.4 °C at a discharge rate of 4 C. • After six extreme cycles, the highest temperature of the battery was recorded 44.8 °C. • GF-NPCM exhibited high thermal conductivity of 1400 W $(m\ K)^{-1}$.	124
PCM with copper metal foam	$LiFePO_4$	Making a battery pack with copper foam-PCM and the insertion of battery into the battery pack for cooling purposes.	• Better temperature reduction can be achieved by copper foam-PCM compared to air cooling and pure PCM system. • It also sustains the temperature uniformity. • Maximum temperature decreased by 6%−13.5%.	125
copper mesh (CM)-enhanced paraffin/EG	$LiFePO_4$ battery	Fabrication of the CPCM plate consists of copper mess with expanded graphite and used in battery pack for cooling purposes.	• Better temperature uniformity and reasonable temperature was maintained compared with traditional ANC and PCMP technology. • Maximum temperature reduced by 9 °C. • Thermal conductivity improves from 0.26 W $(m\ K)^{-1}$ to 7.65 W $(m\ K)^{-1}$.	126

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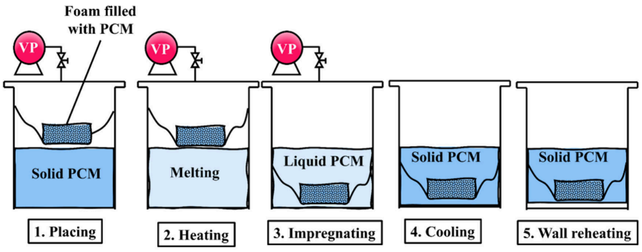

Figure 9. Process flow diagram for vacuum impregnation.

determined to be optimal for the battery's homogeneity and temperature decrease. Additionally, it is established that temperature uniformity benefits most from 5 mm of carbon fiber, whereas 2 mm of carbon fiber was shown to be the most effective. Frusteri and co-workers[107] examined how carbon fibers affected an inorganic PCM to improve heat conductivity. Therefore, a eutectic PCM mixture of Mg (NO_3) was added with a distribution of carbon fibers of varying lengths. The composite's thermal conductivity and $26H_2O{-}MgCl_2{\cdot}6H_2O{-}NH_4NO_3$ were measured using the hot-wire method. The results demonstrated that the enhancement of heat diffusion was significantly attributed to the uniformity of carbon fibers in PCM. Despite the fact that there has been a lot of research on the subject of LIB thermal management, nothing is known about the ideal parameters for these batteries' use in carbon fiber/CPCMs. Thus, it appears that the use of carbon fiber in PCM for LIB heat control is novel in this industry.

Nanomaterials, which are materials with dimensions on the nanometer scale, can improve the thermal conductivity of PCMs by increasing the number of conductive pathways in the material. The addition of nanomaterials also allows for more efficient heat transfer, resulting in faster charging and discharging rates of the PCM. Various nanomaterials, such as carbon nanotubes, graphene, and metal nanoparticles, have been investigated for their effectiveness in enhancing the thermal properties of PCMs. The outcomes of some research works are shown in Table 10, using nanoparticles in PCM. The effectiveness of nanomaterials in enhancing the thermal properties of PCMs is dependent on several factors, including the type, concentration, and size of the nanomaterials. Additionally, the compatibility of the nanomaterials with the PCM must be considered to prevent unwanted phase separation or degradation of the PCM. Karimi et al.[129] enhanced PCM's thermal conductivity by including metal nanoparticles and metal matrix. The battery performance with Ag, Cu, and Fe_3O_4—three different nanoparticles—performed better than with pure PCM. Ag nanoparticles were found to be present in the most persuasive PCM, which lowered the battery temperature differential by 50%. Multiwalled carbon nanotubes (MWCNT) and graphene were employed in PCM-based BTMS by Zou et al.[130] The inclusion of MWCNT and graphene (1% mass fraction) enhanced the thermal conductivity of pure PCM by 41% and 61.5%, respectively. They combined PCM with various mass ratios of MWCNT and graphene, and the greatest improvement was seen when 30% MWCNT and 70% graphene were used. The maximum battery temperature for this improved CPCM was lower than 46 °C. Overall, the incorporation of nanomaterials into PCMs shows promise in improving the thermal properties of these materials for TES applications. To optimize the kind and concentration of nanomaterials for certain PCM applications, as well as to look into the long-term stability and safety of these composite materials, more study is required. In the BTMS that uses PCM, enlarged graphite PCMs are used as a heat conductivity enhancer. The total effectiveness of the BTMS can be raised by combining PCMs with expanded graphite, a highly conductive material, to boost PCMs' thermal conductivity. According to a study by Jiang et al.[131] utilized EG and observed that the incorporation of EG significantly lowers the temperature rise of LIB and significantly increases the thermal conductivity of CPCM. The CPCM also exhibits exceptional BTMS performance with EG mass fractions ranging from 9% to 20%. The effectiveness of BTMS employing the CPCM/EG on a laptop battery pack was assessed by Al-Hallaj et al.[100] The findings showed that BTMS with PCM is smaller and lighter than conventional BTMS. Lin et al.[132] employed graphite sheet and PCM-impregnated EG matrix to simulate and design a passive heat management system for $LiFePO_4$ battery modules. Alrashdan et al.[114] focused on the thermomechanical behaviors of paraffin and EG blocks in relation to the BTMS of LIBs. Goli et al.,[103] claimed that graphene-enhanced hybrid PCM caused a significant shift in the BTMS of LIBs. Mo et al.[133] used 79.5 wt % paraffin, 5.5 wt % expanded graphite, and 15 wt % epoxy resin to create CPCM. To improve convective heat transfer, the CPCM module made up of sleeve-shaped CPCM units has expanded airflow channels and a larger heat transfer surface area, measuring 3.63×10^{-3} m^2. As a result, the unit-assembled component's thermal resistance is noticeably lower than that of a normal cuboid-shaped section by 52.0% and 60.1%, respectively, and its heat flux is increased by a factor of 7 times in either of the cooling and preheating modes. This BTMS performs exceptionally well in cooling tests, regulating the temperature and temperature differential below 40.30 and 2.80 °C at a discharge rate of 3 C, accordingly.

4.2.2. PCM with Metal-Based Thermal Conductivity Enhancer. It has been demonstrated that adding metal-based enhancers to PCMs, such as copper, aluminum, and graphite, can increase their heat conductivity and lead to more effective TES and release. There are several ways to apply these enhancers, such as coating, embedding, and physical mixing. Hu et al.[138] examined a CPCM that is two times more thermally conductive than the original PCM and contains a porous metal. Examined was the effect of the porous structure in the CPCM. The findings showed that the impregnation ratio of the PCM, not the pore size, could adequately explain the latent heat of the phase transition composite. AIN was used with PCM by Zhang et al.[118] to enhance its thermal conductivity. The CPCM was made with different mass fractions of AIN (5%, 10%, 15%, 20%, and 25%), and a 20% mass fraction showed the greatest improvement in thermal conductivity. The maximum battery temperature was decreased employing PCM/AIN mixture by 19.4%, compared to air-cooled BTMS. While introducing metal-based thermal conductivity enhancers has shown promising results, the optimal amount and type of enhancer required for a given PCM depends on various factors, including specific applications, the operational temperature range, and the desired thermal conductivity. In conclusion, the incorporation of metal-based thermal conductivity enhancers can significantly ameliorate the thermal conductivity of PCMs, resulting in more efficient TES application and release heat faster. However, further research is required to optimize the use of these enhancers for various PCM applications.

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Table 10. Outcomes of Some Research Work on Nanoparticles Based BTMs

properties of PCM and NP						
PCM	nanoparticle	method of preparation	battery type	system description	important outcomes	ref
paraffin wax	CuO MWCNT	–	LIB	Fabrication of matrix consists of nanio-particles (CuO, Cu, MWCNT) into PCM for cooling purposes.	• With increasing the volume fraction of the nanoparticle enhances the heat transfer coefficient of the battery.	134
paraffin mixture, T_{mp} = 39−45 °C	Ag Cu Fe_3O_4	two-step	LIB	Inclusion of the metal matrix into the PCM for the passive cooling of the battery.	• ~70% decrease in temperature difference obtained by metal-matrix CPCM. • Ag nanoparticles exhibited better thermal management than others.	129
paraffin wax	graphene	two-step	LIB	Introducing of graphene into PCM with mass fraction 1% and 20%.	• Improvement of thermal conductivity by inserting graphene into PCM and reduced the battery temperature.	103
paraffin	carbon fiber	melt-mixing	LIB	Utilization of carbon fiber into PCM (paraffin) to enhance its thermal conductivity for cooling purposes.	• Optimum thermal performance obtained in a mixture of PCM with 2 mm long carbon fiber and 0.46% of mass percentage. • Around 45% maximum temperature reduction was recorded.	128
paraffin wax, T_{mp}= 38−41 °C	graphene-coated nickel (GcN)	coating and infiltration mixing	18650 LIB	This system was compared to nickel foam, paraffin wax, GcN foam, nickel foam saturated with paraffin, and GcN foam saturated with paraffin. Graphene-coated nickel foam was used to cool saturated paraffin.	• Thermal conductivity enhancement of PCM by ~23 times after inclusion of GcN.	135
paraffin	expanded graphite matrix and graphite sheets	vaccum impregnation	$LiFePO_4$ battery	Fabrication of CPCM with expanded graphite matrix and insertion of battery between the graphite sheets.	• This system can maintain the thermal uniformity into the battery cell. • The maximum temperature difference was kept below 5 °C.	136
$Na_2SO_4 \cdot H_2O$	Al_2O_3	two-step	18650 LIB	Cooling of the battery by using $Na_2SO_4 \cdot H_2O$ with alumina nanoparticles.	• Rise in cell temperature limited to 3 °C.	137

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4.2.3. PCM with Metal Fiber. Metal fibers, such as copper, aluminum, and nickel, have high thermal conductivity and the incorporation of these metal fibers into the PCM can form a composite material. The resulting PCM-metal fiber composite exhibits an increment of thermal conductivity, compared to pure PCM. The heat conductivity of the CPCM can be further enhanced by adding more metal fiber to the PCM, as well as by optimizing its size and distribution. Pan and Lai[139] suggested a novel use for copper fiber/paraffin composite in battery temperature control. They utilized four BTMS—pure PCM, PCM with copper fibers, PCM with copper foam, and natural air blowing—and found that the CPCM made of copper fiber offers effective BTMS. A 28.6% mass percentage of copper fiber was added, resulting in a 1.9 C decrease in the maximum battery temperature. Optimizing the mass fractions of copper fibers (28.1%, 47%, 51.5%, and 60.5%) also enhanced the performance of the battery. The largest temperature declination was found to be displayed by copper fibers with a mass percentage of 60.5%, while the optimal uniform temperature was found to be achieved with a mass fraction of 47% of copper fibers. Taking into consideration both temperature drop and uniformity, the ideal mass fraction of copper fiber was found to be 47%.

For the cooling of LIBs, Zhu et al.[140] combined highly conductive copper microfibrous media with PCM. By using this cutting-edge technology, the battery was able to operate under the harsh conditions of a 15 C discharge rate while keeping the cell temperature below 48 °C. Overall, PCM-metal fiber composites have great potential for use in TES applications, particularly for BTMS. The high thermal conductivity of the metal fibers can improve the efficiency of heat transfer and TES in the composite material, while the high latent heat storage capacity of the PCM can ensure that the stored energy is released as needed. Further research is warranted to optimize the composition and properties of PCM-metal fiber composites for specific applications and to assess their long-term durability and reliability.

4.2.4. PCM with Metal Mesh. The use of metal meshes in PCM-based BTMSs allows for the improvement of heat transfer by increasing the effective thermal conductivity of the system. The metal meshes serve as thermal conductors, helping to diffuse heat more evenly and efficiently throughout the PCM. Moreover, the high surface area of the metal mesh enables better contact with the PCM, facilitating a more efficient heat transfer. These features make metal mesh-based PCM BTMSs more effective at reducing the adverse effects of thermal runaway.

Lazrak et al.[141] investigated the application of PCM and copper mesh in a small prototype battery. They found a 10 °C greater decrease in battery temperature after discharge, compared to a pure PCM system. In order to look into how phase change temperature and thermal conductivity affect battery performance, they also built a three-dimensional (3D) numerical model. They suggested that the ideal alternative would be to select a PCM with strong thermal conductivity whose phase change temperature is close to the battery's safe limit temperature. Wu et al.[126] investigated a CPCM plate that included EG, paraffin, and copper mesh to control the battery pack temperature. The toughness and thermal conductivity of the CPCM were improved by using copper mesh as a framework. At higher discharge rates of 5 C, copper mesh was found to be more effective, and a maximum 5 C temperature drop in the battery was attained. These studies' findings show that metal mesh-based phase change material systems have the potential to enhance LIB temperature management in electric vehicles. To improve these systems' functionality and design, as well as to assess their durability and long-term dependability, more study is necessary.

4.2.5. PCM with Metal Foam. Metal foams are porous materials that possess excellent thermal conductivity, high surface area, and low weight. By embedding PCMs within metal foams, the material's thermal properties can be significantly enhanced, resulting in a more effective BTMS, as shown in Figure 9. Some studies have investigated the use of PCMs with metal foams for BTMS. For instance, Javani et al.[142] conducted a quantitative investigation on the use of *n*-octadecane in polyurethane foam for BTMS. In comparison to dry foam, the results showed that PCM-induced wet foam reduced battery temperature by 7.3 °C. The battery integrated inside the EV was subjected to an experimental examination by Rao et al.,[143] using paraffin/copper foam under road operating conditions. The use of CPCM reduced the battery's highest temperature and temperature differential by 31.4% and 66.3%, respectively. With the help of CPCM, Mehrabi-Kermani et al.[144] created BTMS by mixing copper foam, a heat sink, and a PCM. The results show a significant reduction in the highest battery temperature as well as the temperature disparity. After 40 min of operation without copper foam, the battery temperature was observed to reach 60 °C, but only 53.5 °C even after 100 min with copper foam. Wang et al.[145] used aluminum foam to improve PCM thermal conductivity when it came to battery temperature regulation. The PCM's heat conductivity was increased by 218 times using aluminum foam. The inclusion of CPCM caused temperature decreases of 62.5% and 53%, respectively, at discharge rates of 1 and 2 C. All things considered, combining PCMs with metal foams has been shown to be a viable strategy for raising the effectiveness and performance of BTMS. Subsequent investigations are required to enhance the structure and components employed in these systems and investigate the possibility of utilizing them in many other contexts.

4.3. Nanofluid-Based PCM. Battery cooling performance is mandatory to prevent its explosion and thermal runways. However, the liquid-based cooling such as water and ethylene glycol has a restriction for its low thermal conductivity. Hence, there have been proposed many methods to keep the battery temperature into the desirable range. One of the finest methods is to disperse nanoparticles into liquid to enhance the thermal conductivity of the base liquid. It is found from the research article that the incorporation of the nanoparticles would improve the thermal conductivity of the base fluid. Lee et al.[146] measured the thermal conductivity of the base fluid water and ethylene glycol with the incorporation of CuO and Al_2O_3 nanoparticles and observed that the enhancement of thermal conductivity of ethylene glycol was noticed more than 20% at 4% of volume fraction of CuO nanoparticle. The enhancement of thermal conductivity occurs due to the fact of Brownian motion (constant and random motion of nanoparticles in base fluid) of the nanoparticles into the base fluid.[147] In addition to Brownian motion, several other processes influence convective heat transfer. These include collisions between molecules in the base fluid, thermal diffusion of nanoparticles in the fluid, and the thermal interaction between nanoparticles and base fluid molecules.[148] However, it has drawbacks for its difficult maintenance, high initial cost, and complicated system.[149,150] Researchers have

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Table 11. Summary of Recent Works on Nanofluid-Based BTMS

authors	base fluid and nanoparticle	battery type	system description	important outcomes	ref
Jilte et al.	water and Al_2O_3	18650 LIB	cooling of the EV through liquid-filled battery cooling systems (LfBS) and liquid-circulated battery cooling systems (LcBS) with circulating base water and nanofluid.	• temperature uniformity of battery can keep higher in the liquid circulated system compared with liquid filled. • conditioned cooled air must circulate from the cabin of the EV in order to exchange heat from the circulated liquid during a hot climate.	154,155
Sarchami et al.	deionized water and Al_2O_3	8650-type LIB	cooling of the LIB by flowing 2% volume of alumina nanofluid with flow velocity 0.4 m/s through stair channel.	• This technology can maintain the peak temperature and temperature difference within 305.13 and 2.01 K respectively.	156
Tousi et al.	water and AgO	two cylindrical 18650/21700 LIB	Cooling of the 2 cylindrical 18650/21700 LIB by using AgO nanofluid with different flow rates and volume fractions.	• Performance of reducing the battery pack temperature of 21700-type LIB is better than 18650-type LIB. • With enhancing the inflow velocity and volume fraction of nanofluid decreases the peak temperature and temperature difference.	157
Xu et al.	EG (ethylene glycol) and CuO	cylindrical and square battery pack	Cooling of the cylindrical and square battery pack by using three coolants such as CuO-EG, Al_2O_3-EG, and TiO_2-EG.	• CuO-EG nanofluid can exhibit better performance as coolant for cylindrical battery pack whereas Al_2O_3-EG nanofluid for square battery pack.	158
Kiani et al.	deionized water and Fe_2O_3	LIB	This configuration consists of hybrid system including CPCM, nanofluid cooling and heat sink subjected to magnetic field.	• This system can maintain the temperature of the cell 318.7 K at a Reynolds number of 1250. • The maximum reduction in cell temperature was recorded at ~7 °C and the temperature difference of this hybrid system 4 °C.	159
Sefidan et al.	water and Al_2O_3	18650 LIB	Cooling of the 18650 LIB by submerging it into the aluminum container filled with Al_2O_3-water nanofluid and circulating air for extracting heat through the container.	• Uniformity of the temperature was maintained by this cooling method. • Maximum reduction in temperature was recorded by 16−24 K. • Maximum cell temperature was recorded at ~308 K.	160
Wiriyasart et al.	water and TiO_2	444 cylindrical 18650-type LIB	Cooling of the 444 cylindrical LIB of EV battery cooling module by flowing nanofluid through the corrugated mini channel.	• The maximum temperature declination of the battery cell was observed around 27.59%.	161
Wu and Rao	Water and Cu	LIB	Cooling of the LIB by using Cu-water nanofluid and simulating the model for obtaining temperature distribution.	• The reduction of maximum cell temperature was achieved around 6.5% with 6 vol.% of nanofluid at the Reynolds number 3×10^5.	162
Huo and Rao	Water and Al_2O_3	5 batteries in series	Cooling of the LIB by using Al_2O_3-water-based nanofluid and lattice Boltzmann (LB) model was developed for the simulation.	• The reduction of average temperature was recorded 7% with a volume fraction of 0.04 compared with a water-based system.	163
Mondal et al.	Water, ethylene glycol−water mixture and Al_2O_3 and CuO	LIB with 20 cells	A configuration having 20 prismatic cells partitioned into 2 or 4 stacks and flowing the pure water or mixture of water and EG along with the inclusion of Al_2O_3 at 1% and 4%.	• The performance in the case of temperature reduction is better for pure water-based systems than others. • Inclusion of nanoparticles into the base fluid does not have a positive effect on battery temperature except having an impact on thermal conductivity.	76

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proposed nanofluid, which is prepared through uniform mixing of nanoparticles into the base liquid.[151] Nanofluids were prepared by the inclusion of nanoparticles like ZnO, Al_2O_3, TiO_2, CuO into the base fluid (water and ethylene glycol).[152] Table 11 presents the summary of recent works for battery cooling purposes by using nanofluid. Mitra et al.[153] developed a nanofluid by adding MWCNTs to ethylene glycol and water at three distinct fractions of volume (0.15%, 0.3%, and 0.45%). They then compared the cooling properties of the nanofluid to that of water and the ethylene glycol−water mixture. The battery cells' mean temperature drops to a maximum of 6.9, 10.2, and 11 °C at 2.1 °C in single-channel flow, dual-channel parallel flow, and dual-channel counter-flow arrangements, respectively, at 0.45% volume fractions of MWCNTs. Dual-channel with counter-flow system offers the best performance, with regard to temperature drops in the range of 8.6−13 °C.

5. THERMAL MANAGEMENT USING FINS

The battery case is connected to thin, expanded surfaces called fins. They enhance the battery's surface area, facilitating increased convectional heat dissipation. Heat from the battery is transported to the fins, which release the heat into the surrounding atmosphere. A schematic diagram of the PCM-based BTMS with a biomimetic fin is shown in Figure 10.

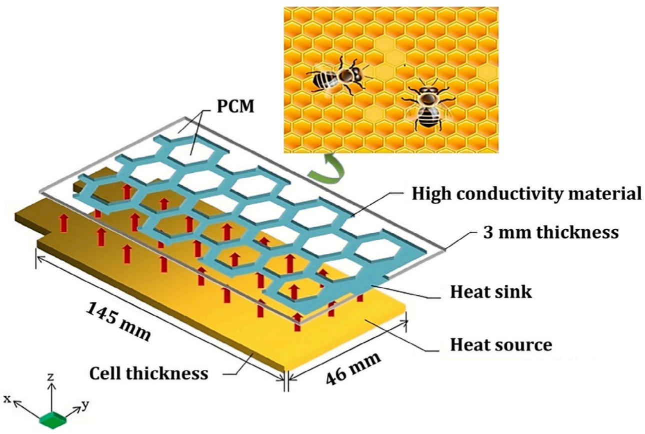

Figure 10. Schematic diagram of PCM battery cooling system with biomimetic fin. [Reproduced with permission from ref 168. Copyright 2021, Elsevier.]

Several aspects need to be taken into account when designing a fin-based BTMS. These include the size and shape of the fins, the material used to construct them, and the placement of the fins on the battery casing. According to studies, well-designed fins can considerably increase a battery's thermal performance, lowering the possibility of overheating and lengthening its life. Additionally, fin-based thermal management systems can be combined with other techniques, such as PCM or active cooling systems, to further improve battery performance and reliability.

Expanded surfaces can be used to improve the area available for heat transmission and address the issue of PCM's low thermal conductivity. Additionally, some researchers have used fins within PCM-based battery packs to improve the heat regulation. Zhong et al.[164] used CPCM and metal fins inside the battery cell. Even in the presence of an intense 40 °C ambient condition and a high discharge rate of 5 C, the highest temperature was maintained below 45 °C with a temperature differential of no more than 5 °C. Experimental research on the impact of fins and PCM on prismatic battery performance was conducted by Ping et al.[165] With fins installed, the highest battery temperature was kept below 65 °C even at a high discharge rate of 3 C. They also developed and evaluated a computational model for PCM-fin-based BTMS. Thinner fins, optimal fin spacing, and thicker PCM layers were found to be effective when the impacts of fin thickness, spacing, and thickness were examined. The cylindrical prototype battery cells with longitudinal fins are studied by Sun et al.[166] After testing the effect of fin count with 4, 8, and 12 fins, it was found that eight fins were the best option; additional fins improved the heat transfer area but produced less PCM. Heyhat et al.[167] studied a numerical model to analyze how fins with PCM affect battery performance. They focused on the fin count (1, 3, and 5) and realized that having more fins did not necessarily translate into an advantage. The maximum battery temperature dropped by 2 and 4 °C, respectively, with heat generation rates of 4.6 and 9.2 W. Fin utilization was also compared to the use of metal foam and nanoparticles. The metal foam proved to be the most effective, even though fins and nanoparticles were found to be more efficient. The literature indicates that most investigations have focused on longitudinal fins, with only one researcher testing circular fins. However, further research into the combination of many shaped fins, an ideal layout, or creatively made fins must be required.

5.1. Effects of Internal Fin Shape in the PCM Module.

The internal fin shape of the PCM module, as shown in Figures 11 and 12, has a significant impact on its thermal performance, because it influences the rate of heat transfer and the quantity of energy that can be stored or released by the PCM during phase shift. Several researchers have examined the implications of an internal fin shape on PCM module performance. For instance, Weng et al.[169] illustrated in Figure 12 the impact of fins of various shapes on the PCM-based BTMS. The two forms of rectangular, triangular longitudinal fins, as well as circular fins, were explored. When the natural convection approach was utilized to disperse heat from PCM, it was observed that longitudinal fins more effectively reduced the battery temperature. In addition, they reported an optimized design with circular and longitudinal fins, with

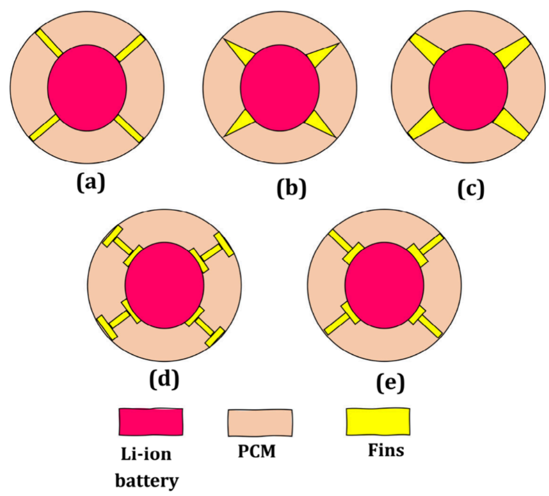

Figure 11. Types of fins (a) rectangular fins, (b) triangular fins, (c) trapezoidal fins, (d) I-shaped fins, and (e) T-shapd fins. [Reproduced with permission from ref 170. Copyright 2020, Elsevier.]

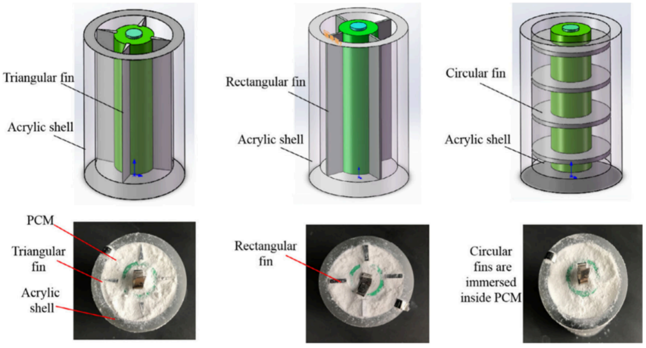

Figure 12. Stereograms and corresponding experimental images of the placement of the three fin cases. [Reproduced with permission from ref 169. Copyright 2020, Elsevier.]

circular fins inserted in the bottom portion and longitudinal fins in the other portions. The enhanced design of this structure resulted in a 5.5% reduction in the highest battery temperature, as compared to the previous rectangular finned construction.

Choudhari et al.[171] investigated the use of fin construction in the PCM module by raising the total number of fins for improved heat transfer and utilizing a variety of fin forms, including rectangular, triangular, trapezoidal, I-shaped, and T-shaped fins. The battery temperature decreases by 2 and 6.4 °C at discharge rates of 2 C and 3 C, respectively, as a result of the fin arrangement of the PCM module incorporation. Furthermore, it reduces the temperature differential between the PCM and battery from 3.36 °C to 1.78 °C, as a result of the PCM's improved conduction quality. A comparison graph of the temperature difference between LIBs and PCM containing different types of fins is plotted in Figure 13. The majority of fin structures exhibit minimal variations in their behavior concerning battery temperature. Nonetheless, I-shaped fins are the most efficient and triangular fins are the least efficient when it comes to temperature difference as reported in Figure 13. While circular fins have a greater capacity for heat conduction within the PCM due to their larger heat transfer area, and longitudinal fins are superior for heat dissipation by air convection.

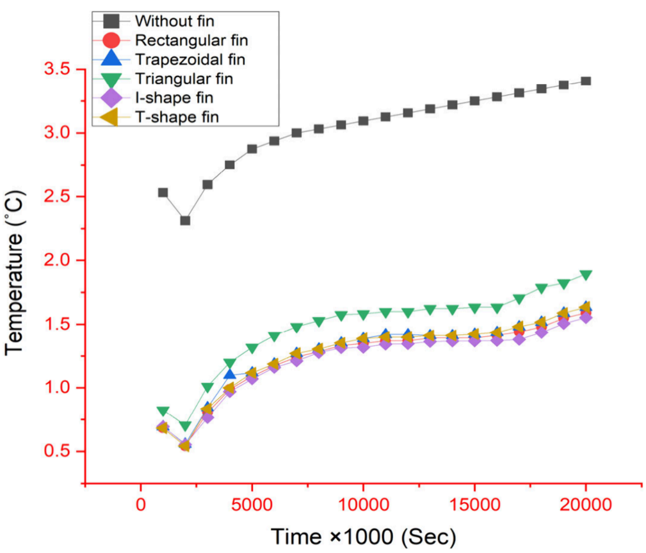

Figure 13. Temperature difference between LIB and PCM containing different types of fins. [Reproduced with permission from ref 170. Copyright 2020, Elsevier.]

5.2. Effects of Fin Number in the PCM Module. Numerous researchers have examined the influence of fin count and fin arrangement on the performance of PCM-based thermal systems.[172−174] Figure 14 shows a typical arrangement of the battery module with fins. These investigations demonstrate that the addition of fins can efficiently reduce battery temperature due to the fact that increasing the number of fins increases the thermal conductivity through PCM. Adding more fins will result in an increase in fin area, higher expenses, and a reduction in PCM in the structure as a whole. This reduction in PCM volume could reduce the PCM module's ability to store heat. The PCM module must have the optimal number of fins in order to maximize heat transmission. Furthermore, the suggested fin intensified systems might function well, even in hot weather. In comparison to the PCM system, the equivalent working time rose by 1.48, 1.49, and 1.81 times at ambient temperatures of 20, 30, and 40 °C, respectively.[175] This indicates that the fin-enhanced PCM systems outperform the PCM systems.

Using numerical simulations, Jiao et al.[176] examined the thermal effectiveness of a PCM module with varied numbers of fins. According to the study, increasing the number of fins from four to eight enhanced the cooling performance of the module by ∼10%. In a similar study, Liao et al.[177] studied the thermal properties of a PCM module with varying fin numbers and discovered that increasing the number of fins from 4 to 8 reduced the battery's maximum temperature by 25%. A figure of a PCM module with different numbers of fins is represented in Figure 15 and the temperature deviation of a battery having several fins (see panels (a) and (b)) is shown in Figure 16 (presented later in this work). It is found that when the number of fins is raised to four, the temperature decreases by between 2 and 6.1 °C.[170] However, the temperature drop decreases as the number of fins grows, from 0.6 to 1.9 °C when the number of fins increases from 4 to 6.

5.3. Effects of External Heat-Transfer Coefficient in the PCM Module. The size, shape, and orientation of the PCM module, as well as the environmental factors like temperature, thermal conductivity, and fluid flow velocity, all affect the value of this coefficient. The PCM module's temperature distribution, charging and discharging rates, and overall system efficiency are all determined by the external heat-transfer coefficient. The impact of the external heat-transfer coefficient on PCM-based TES system performance has been the subject of several studies. An experiment that was carried out by Chen et al.[178] revealed that the temperature of heat-transfer fluid and flow rate has significant impacts on charging and discharging rates. The effects of PCM module geometry and orientation on the temperature distribution and heat-transfer coefficient within the PCM were found quantitatively in certain investigations. The researchers came to the conclusion that using fins or rotating the PCM module can significantly increase the outside heat-transfer coefficient. The impact of the exterior heat-transfer coefficient on performance has been investigated by researchers. For example, Wang et al.[179] assessed the impact of fin thickness and fin spacing on a PCM module's heat-transmission coefficient and melting process. They found that the PCM melting process was hastened by increasing the heat-transmission coefficient and decreasing the fin spacing. It was attempted to construct the PCM module with various exterior

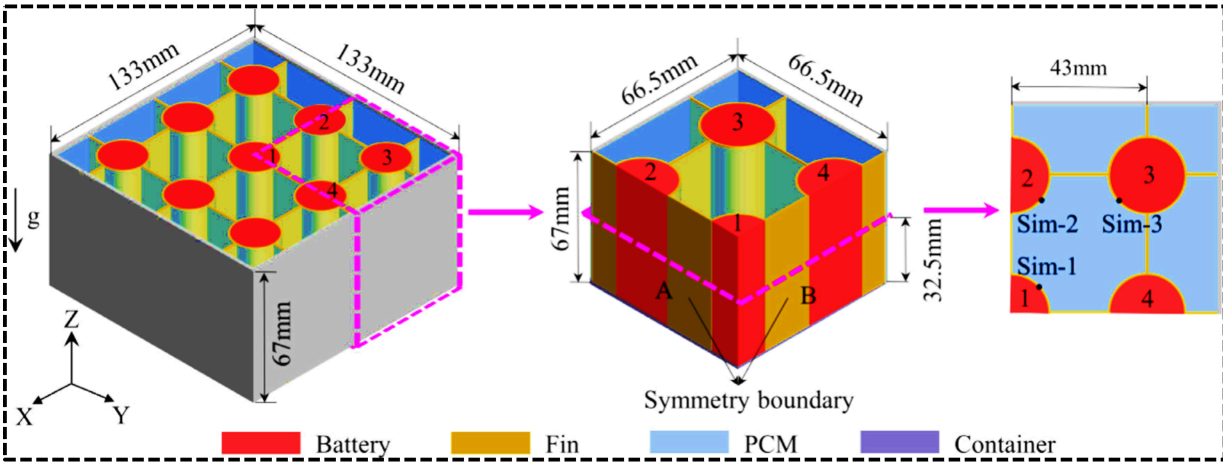

Figure 14. Arrangement of the battery module. [Reproduced with permission from ref 175. Copyright 2021, Elsevier.]

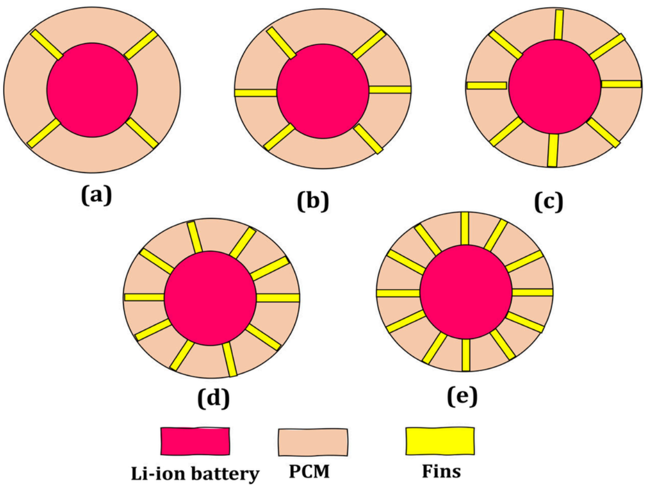

Figure 15. PCM module with different number of fins: (a) 4, (b) 6, (c) 8, (d) 10, and (e) 12. [Reproduced with permission from ref 170. Copyright 2020, Elsevier.]

heat-transfer coefficients on the temperature of the LIB. The heat-transfer coefficient of the LIB increases from 5 W m^{-2} K^{-1} to 15 W m^{-2} K^{-1}, while the battery temperature drops quickly from 4.8 °C to 25.6 °C (at discharge rates of 2 and 3 C, respectively).[170] However, there was a slight drop in temperature afterward.

5.4. Effect of Type of Branch Structured Fins. Branch structured fins are a form of expanded surface that provides increased heat-transfer area and can be utilized to improve BTMS heat dissipation. The effect of different forms of branch structured fins, such as tree-like fins, Y-shaped fins, and X-shaped fins, on BTMS performance has been explored. Battery module with only PCM for cooling purposes exhibits lower heat dissipation from the battery to the ambient, particularly in the high temperature environment or hot region due to the low thermal conductivity of PCM and suffer from heat-storage saturation after three or four cycles. Hence, the thermal energy is entrapped into the battery module for having a low heat dissipation attribute and so only traditional fin with single heat flow channel is not sufficient to cool the battery at the required range for enhancing the performance of the battery cell. Therefore, Weng et al.140 proposed a different shape of fins, including rectangular fin (single heat flow channel), V-shape (two heat flow channel), Y-shape (three heat flow channel), and X-shape (four heat flow channel) to enhance the heat-transfer area for higher heat dissipation from the battery cell to the ambient, as depicted in Figure 16. In this study, the authors

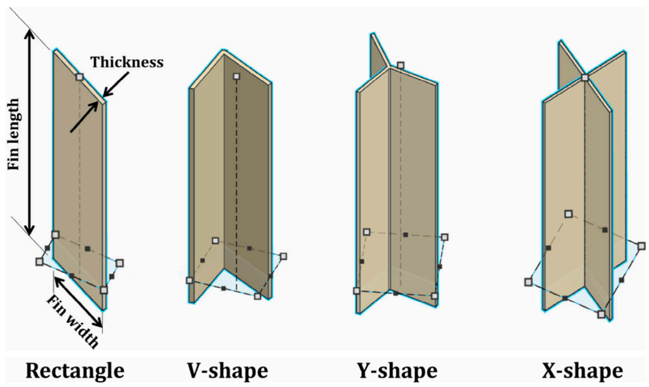

Figure 16. Schematic diagram of different branch structures of fins. [Reproduced with permission from ref 180. Copyright 2019, Elsevier.]

observed that, by keeping the highest cell temperature below 47 °C in a high temperature environment of 40 °C, the X-shape demonstrated the highest performance. Hence, the novel fins having the higher number of heat flow channels with higher surface area improve the cell performance and the efficacy of BTMS. In addition, researchers have investigated the usage of several materials for branch structured fins. The type of branch structured fin and the material employed have a substantial impact on the heat-transfer efficiency of BTMSs.

5.5. Effects of the Position of the Cylindrical Ring. The configuration, organization, and spacing have a substantial impact on the thermal safety of the LIB pack.[181] For a Li-ion BTMS that uses PCMs, the cylindrical ring's location is an important design factor. The BTMS's performance could be significantly impacted by the cylinder ring's positioning, especially in terms of heat-transfer rate and battery temperature distribution. The effect of the ring's radial position has been investigated by several researchers. The dimensionless distance of the ring (d^*), which is the ratio of the radial distance of the ring to the diameter of the battery, indicates the position of the cylindrical ring. Sun et al.[166] assessed four dimensionless distances of the ring (d^* = 0, 0.1, 0.2, and 0.3)

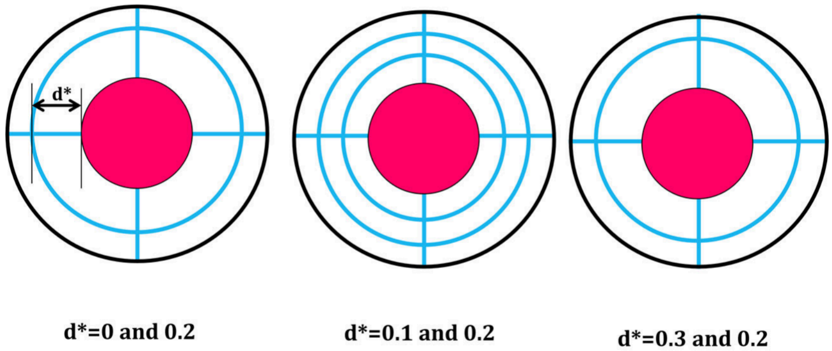

Figure 17. Schematic of the position of the cylindrical ring. [Reproduced with permission from ref 166. Copyright 2019, Elsevier.]

in their experiment. Figure 17 shows a schematic of the cylindrical ring's location and changes in the battery's surface temperature over time at various ring positions.

A larger ring is applied as the distance increases, prolonging the battery's life and preserving its temperature. It seems that the performance of heat management is improved by using a larger ring. However, when the dimensionless distance approaches 0.3, the battery life starts to drastically decrease. There are two variables that could be the cause. One is that using a large ring result in the ring's volume expanding, which lowers the PCM in the BTMS; the other is related to the ring's reduced ability to transfer heat.

5.6. Effects of the Number of Longitudinal Fins. One of the most popular methods for improving heat transfer in cylindrical batteries is the introduction of longitudinal fins. The impact of the quantity of longitudinal fins on the thermal behavior of LIB has been the subject of numerous investigations. Sun et al.[166] analyzed the ideal quantity of longitudinal fins needed to improve a cylindrical battery's thermal performance and reported that the highest battery temperature decreased as the fin count rose. Furthermore, it was discovered that seven fins were the ideal quantity.

6. OPPORTUNITIES AND CHALLENGES

Battery thermal management typically uses the PCM cooling system, because of its improved temperature control and equitable distribution. It is commonly known that maintaining LIB's high energy power density contributes to EV and HEV driving range extensions. Therefore, a high-efficiency BTMS can be achieved by decreasing the system weight and increasing the energy density. The weight and volume of the overall power system progressively rose with traditional PCM modules, especially those with large PCM blocks and matrices, which greatly decreased the energy density. To address the previously described problem, new lightweight PCMs and PCM-BTMSs must be created in unique shapes. Furthermore, research on PCM-based BTMS is still in the experimental stages, in contrast to more well-established methods of liquid and air cooling.[182]

The established PCM-functioning packs of batteries and fin setups are also in the sample stage and have not been pushed for use in real-world electric vehicle applications. By enhancing the PCM thermophysical characteristics and PCM-based BTMS, particularly efficacy optimization, structural design, space, weight, cost, energy consumption, and cooling efficiency, the manufacturing of PCM-based battery modules can be accelerated. High-density power batteries require more than one PCM heat-transfer system to suit their heat-dissipation needs.[183] For the time being, future progress will inevitably be governed by the more-efficient hybrid cooling systems based on PCM that integrate active and passive cooling technologies. Based on their key characteristics, the active and passive components of the composite cooling system each have unique benefits. The complementing system will effectively remove the heat that has been collected in the PCM heat-dissipation medium, enhancing the material's capacity to store and release heat as well as extending its cycle life and efficiency of use for overall performance and safety.

The BTMS's usefulness was severely constrained by the practical applications' large disregard for structural stability issues. Phase change component precipitation/leakage, insufficient mechanical characteristics, CPCM matrix deformation, and long-term/hard operating EV/HEV cycles were among these problems. A unique method that is utilized to create certain shape-stabilized PCM with pure paraffin (PA) and supporting matrices can be employed to tackle these issues. Using carbonaceous additives, plastic/metallic skeleton systems, and supporting polymer substrates such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene, and epoxy resin, form-stable CPCM can be made to maintain its shape and stop leaks during phase change periods.

It has been discovered that the battery's thermal performance improves with increasing PCM content since the material can store more heat. However, there is a limit on the battery pack's internal PCM replenishment capacity. Furthermore, when the quantity of PCM rises, the battery pack's weight also increases. Consequently, consideration must be given to weight and space constraints while inserting PCM into the battery pack. A variety of PCM-based hybrid BTMS approaches exist, including PCM/TE, PCM/HP, PCM/liquid, and PCM/air cooling. Regarding cost, weight, degree of integration, availability of space, and service life, each of these systems has merits and limitations. This means that when developing a logical design and establishing a suitable thermal management system, the requirement for heat disposal under realistic loading conditions must be taken into consideration.

Research has used PCM in combination with metal fins to increase the area of heat transmission and compensate for the low thermal conductivity of the material. The research participants made several attempts to add more fins in an effort to improve battery performance. More fins are known to enhance the surface area available for heat transfer, but they also prevent convection from occurring naturally. Therefore, the number of fins should be selected as optimum for the best

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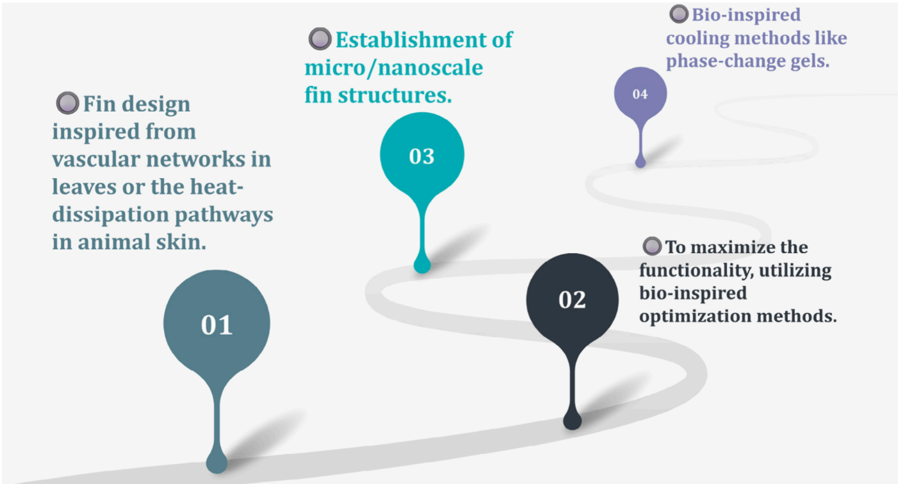

Figure 18. Schematic outlining the future research path of CPCM-based BTMS.

battery operation. In battery thermal management applications, longitudinal and circular fins are typically utilized in conjunction with PCM. However, studies must concentrate on developing innovative shapes, such as spiral fins, with optimal placement.

7. FUTURE RESEARCH DIRECTIONS

A schematic representation of the future research propositions is reported in Figure 18. For the purpose of creating improved PCM composites, research into natural materials and architectures (such as the honeycomb structure, nacre, or lotus leaves) can improve thermal conductivity, mechanical strength, and overall thermal management performance. The establishment of microscale/nanoscale structures that optimize heat transport within the PCM modeled after naturally occurring, effective heat exchangers, such as the vascular networks in leaves or the heat-dissipation pathways in animal skin. Battery temperatures can be dynamically controlled by the design of adaptive systems influenced by biological temperature regulation mechanisms, such as water retention in humans or thermoregulation in reptiles. Furthermore, the creation of smart control systems for real-time thermal management involves the integration of biomimetic algorithms, which imitate natural processes like the neural networks in the human brain. Regarding hybrid systems which operate better, combine PCM-based systems with other bioinspired cooling methods like phase-change gels (which resemble the structure of jellyfish) or evaporative cooling (which, in turn, is inspired by animal panting). To improve passive cooling expertise, PCM can be integrated with natural ventilation systems that are modeled after termite mounds or bird nests. In addition, research can be done on bioinspired PCMs that have superior thermal stability, higher latent heat, and quicker phase change rates. To develop sustainable BTMS, investigation can be made on biodegradable and environmentally acceptable PCMs that are modeled after natural waxes, oils, and gels. The creation of biomimetic-based computer models and simulations to forecast PCM-based BTMS performance and behavior within varied operating scenarios. Finally, to maximize the functionality and design of BTMS, bioinspired optimization methods such as swarm intelligence or genetic algorithms may prove applicable.

8. CONCLUSIONS

BTMSs based on PCMs have become a prevalent research topic due to their ability to manage battery temperature and limit the risk of thermal runaway. The various cooling technologies—air-based, liquid, PCM, PCM with fins, CPCM, nano-PCM, and nanofluid-based cooling systems—were covered and highlighted in this Review. The causes of battery thermal runaway, with a focus on LIBs used in EV, as well as its detrimental impacts, have been highlighted in this article. The significance of the BTMS and its various approaches have since been examined and shown. Numerous studies have examined and determined that both pure PCM-based and CPCM-based BTMS are efficient at controlling battery temperature. The use of a PCM in the BTMS is beneficial as it reduces the temperature fluctuation of the battery and thus prolongs the life and improves the battery performance. CPCM has a higher melting temperature and latent heat compared to the individual PCM components, making it more effective in absorbing and liberating heat during the charging and discharging processes of the battery. Moreover, the use of fins, nanofluid and nano-PCM has also been found to be an efficient way to cool down the battery. A comprehensive review of different methods has been highlighted for the cooling purposes of the battery cell and the major conclusions are drawn as follows:

- Phase change material can protect the battery cell from overheating due to the increase in temperature. HP combined with beeswax and RT 44HC lower the battery surface temperature by ~31.9 and 33.2 °C, respectively.
- The battery performance can be enhanced by incorporating composite material into PCM. The maximum battery temperature and cell differential temperature can be limited by 45 and 5 °C, respectively, by using a kaolin/EG/ paraffin composite at a discharge rate of 4 C.
- Thermal conductivity of the PCM can substantially be enhanced by incorporating graphene-coated nickel. Additionally, the study revealed that an ~70% decrease in temperature difference can be obtained by introducing metal matrix composite into paraffin.
- Only base liquid (water and ethylene glycol) cannot dissipate the higher heat from the battery cell. Hence, nanofluid is introduced over the base liquid for

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enhancing thermal conductivity of base liquid. This was demonstrated by a study used deionized water and Al_2O_3 for cooling purposes of LIB (8650 type) and successfully restrained the peak temperature and temperature difference by ~32 and 2.01 °C, respectively.
- The development of advanced heat-transfer technologies such as microchannel heat exchangers and TECs can enhance the performance of BTMS.

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Notes

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Hussein A. Mohammed obtained his B.Sc. and M.Sc. degrees from Baghdad University, Iraq. He holds two Ph.D. degrees; the first Ph.D. was obtained from Universiti Tenaga Nasional, jointly with the University of Southern Queensland, and the second one in chemical and renewable energy was obtained from Curtin University, Australia. Dr. Mohammed is a Senior Lecturer at the School of Engineering, Edith Cowan University, Australia. His research interests include renewable energy, phase change materials, nanotechnology, miniature cooling, batteries, etc.

NOMENCLATURE

$Al_2\ O_3$ = aluminum oxide
ZnO = zinc oxide
$LiCoO_2$ = lithium cobalt oxide
$LiMn_2\ O_4$ = lithium manganese oxide
$LiNiMnCoO_2$ = lithium−nickel manganese cobalt oxide
$LiFePO_4$ = lithium iron phosphate
$Li_4\ Ti_5\ O_{12}$ = lithium titanate
TiO_2 = titanium dioxide

ABBREVIATIONS

EV = electric vehicle
LIBs = Li-ion batteries
BTMS = Battery Thermal Management System
TR = thermal runaway
SEI = solid electrode interlayer
PCM = phase change material
HP = heat pipe
OEM = original equipment manufacturer
HEV = hybrid electric vehicle
DOD = depth of discharge
Ah = ampere hour
TMS = Thermal Management System
CPCM = composite-PCM
TES = thermal energy storage
EG = expanded graphite
AlN = aluminum nitride
PA = paraffin
APP = ammonium polyphosphate
RP = red phosphorus
ER = epoxy resin

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MWCNT = multiwalled carbon nanotubes
LfBS = liquid-filled battery cooling system
LcBS = liquid-circulated battery cooling system
LDPE = low-density polyethylene
HDPE = high-density polyethylene
TE = thermoelectric

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