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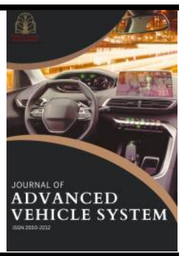
Journal of Advanced Vehicle System

Journal homepage:
https://karyailham.com.my/index.php/javs/index
ISSN: 2550-2212



A Comprehensive Systematic Review of the Cooling Technique for Battery Thermal Management Systems in Electric Vehicles

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ARTICLE INFO

Article history:
Received 28 November 2024
Received in revised form 1 December 2024
Accepted 13 February 2025
Available online 20 March 2025

Keywords:
Electric vehicle battery thermal management system; cooling method; phase change material

ABSTRACT

As electric vehicles (EV) become more and more popular, effective battery thermal management systems (BTMS) are essential for maintaining battery longevity, improving performance, and ensuring safety. Battery action generates much heat, which makes this process difficult. Heat management is needed to reduce the negative effects of high heat. Many cooling methods, including liquid cooling, air cooling, and phase change materials (PCM), have been thoroughly studied. Recent studies on BTMS cooling methods for cars are reviewed in this paper. A comprehensive analysis of research published between 2022 and 2024 was conducted using a structured methodology. These include databases such as Scopus and Web of Science (WoS). The review examines various cooling methods and emphasizes important factors such as energy saving, temperature uniformity and maximum temperature drop. Numerical findings show that hybrid systems, especially those combining liquid cooling and PCM, show exceptional thermal performance. This system improves temperature uniformity and stability, which is essential for optimal battery performance. When forced air cooling is combined with liquid cooling and PCM, cooling efficiency and energy consumption increase significantly. The results show that using a hybrid cooling system is the most effective BTMS method for electric vehicles. Future research should focus on additional optimization and practical testing to evaluate this advanced cooling system under various operating situations. This comprehensive evaluation facilitates the development of a more durable and effective BTMS, which enables the development of safer and more reliable electric cars.

1. Introduction

The automotive industry has undergone a significant transformation as a result of the increased adoption of electric vehicles (EVs) in response to increased demand for greener and more environmentally friendly transportation options [1-3]. As the use of EVs increases, efforts to improve

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https://doi.org/10.37934/javs.16.1.2349

the performance, safety and reliability of EVs have increased. The setup of a Battery Thermal Management System (BTMS) that is effective is crucial to maintaining ideal battery temperatures [4] and guaranteeing durability [5], effectiveness [6], and safety of the battery packs [7] at the center of these improvements. EVs operate through batteries, which provide energy for propulsion. However, lithium-ion batteries, which are the main source of EV power, generate a lot of heat during operation. Both in terms of performance and lifespan, these batteries are very sensitive to temperature changes. Excessive heat can cause thermal runaway, a dangerous condition when the battery overheats uncontrollably and can cause a fire or explosion [8-14]. Using the battery in very cold climates, on the other hand, can cause the battery capacity and speed to decrease. Therefore, maintaining the battery temperature in an appropriate range is important, and a sophisticated BTMS is required to control heat dissipation well [15-17].

Creating a successful BTMS involves a number of difficulties. The system has to be able to control the amount of heat produced in different operating modes, such as charging, discharging, and idling. To avoid localized overheating, an equal temperature distribution inside the battery pack's cells must also be provided. In order to prevent a major drain on the vehicle's power resources, the BTMS has to be lightweight, energy-efficient, and reasonably priced to be widely used [18-20]. Every technique has pros and cons that affect which applications within the EV landscape they are appropriate for. One of the simplest and least expensive ways is air cooling. In order to disperse heat, air must be circulated in the battery pack. Fans may be utilized to improve airflow in both forced and natural convection methods of implementing this technique. Even while air cooling systems are lightweight and simple to maintain, they are not as effective at cooling down high-performance EVs that produce as much heat as alternative cooling systems [21]. Figure 1 shows the current trend of cooling techniques for BTMS.

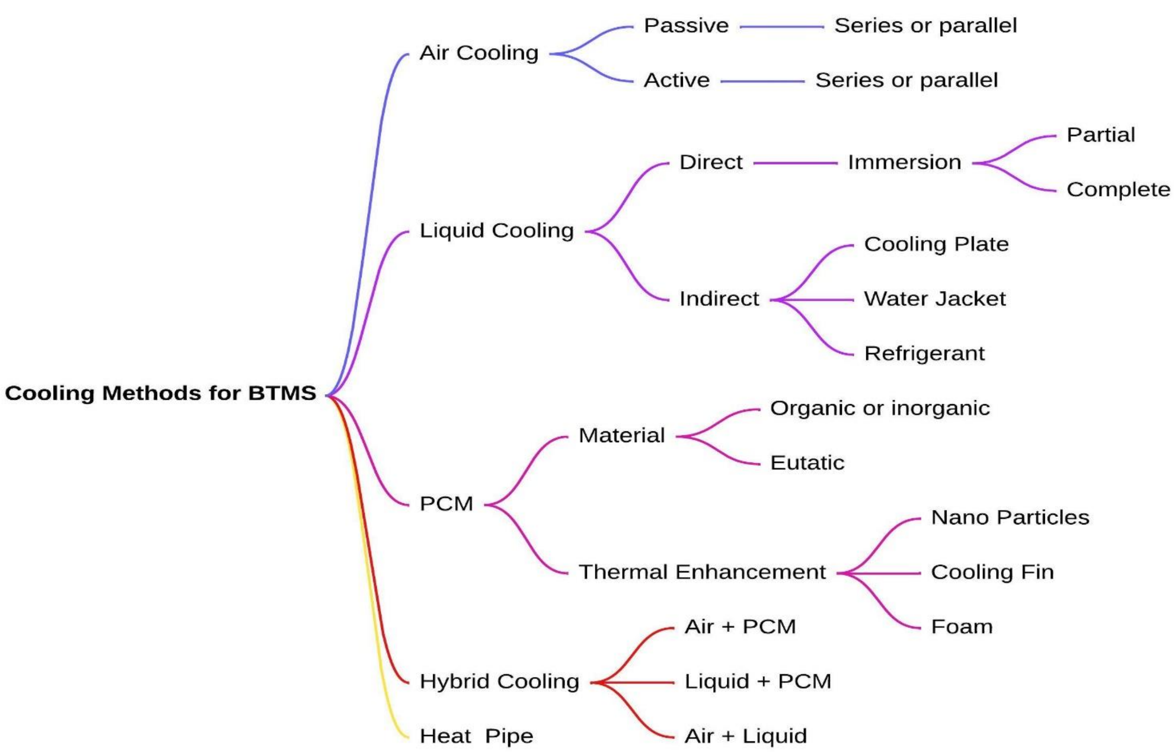


Fig. 1. Current trend cooling techniques for BTMS

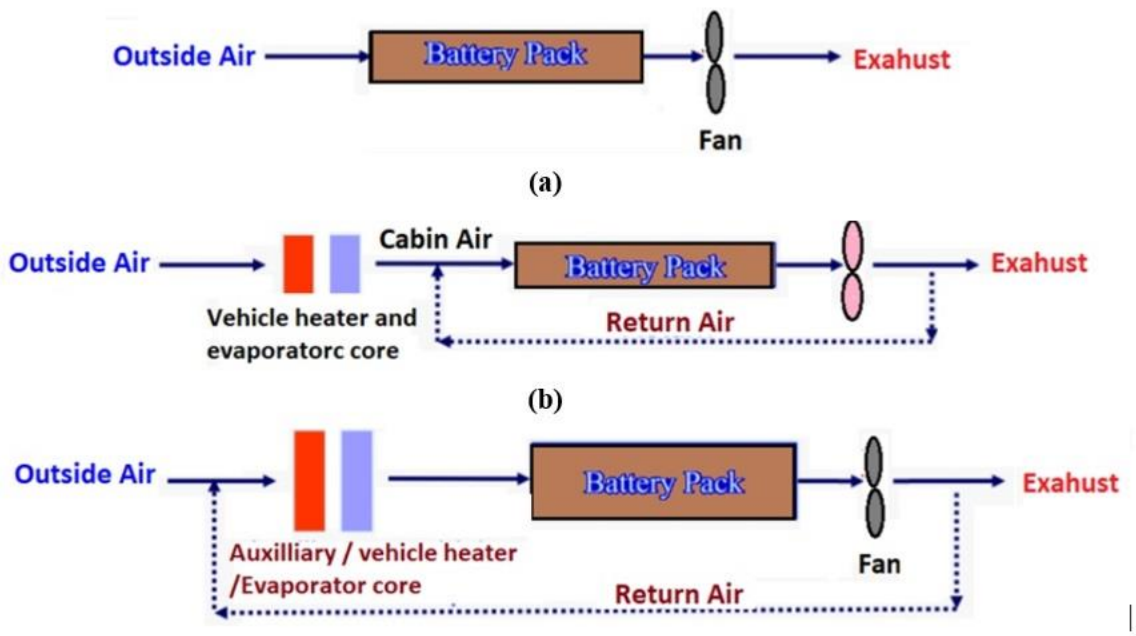
The greater heat capacity and thermal conductivity of liquids make them a more efficient cooling method than air cooling. Via pipes set into or surrounding the battery pack, these systems circulate coolant, which is usually a combination of water and glycol. Heat is transferred from the batteries to the liquid and then dissipated through a radiator [22]. Liquid cooling systems provide superior thermal management and are capable of maintaining a uniform temperature distribution. However, they are more complex and heavier and require robust sealing and maintenance to prevent leaks [23]. During phase changes (such as from solid to liquid), phase change materials (PCMs) use materials that can absorb and release thermal energy. Thermal energy is stored by the PCM, which absorbs heat and melts when the battery temperature rises. The stored energy is released when the PCM hardens due to cooling [24]. A relatively constant temperature may be maintained during phase shift using PCMs, which also offer excellent energy storage density. However, due to problems with the material's volume change during phase transition and the requirement for effective thermal conductivity to promote heat transmission, its implementation can be difficult [25].

Hybrid cooling systems combine many approaches to take advantage of each one. For example, a hybrid system may combine PCM and liquid cooling to ensure steady-state cooling while delivering effective heat absorption at peak loads. Although these systems can provide better heat control, they are frequently more expensive to build and operate. Next-generation BTMS is being made possible by developments in thermal engineering and materials science. Engineered colloidal suspensions of nanoparticles known as nanofluids are being investigated for their improved thermal characteristics in liquid cooling systems. Furthermore, sophisticated sensors and artificial intelligence are being used in the development of smart thermal management systems that will constantly modify cooling plans in response to actual battery conditions [26-28]. In conclusion, as the market for EVs expands, BTMS development will be essential to resolving the issues with thermal management brought on by high energy density batteries. In order to guarantee the longevity, performance, and safety of EV batteries, future BTMS advancements are probably going to concentrate on increasing efficiency, cutting costs, and incorporating sophisticated control systems.

2. Literature Review

For EVs, the development and improvement of BTMS is essential to guaranteeing battery longevity, safety, and performance. Many cooling methods have been investigated in numerous research; each has particular advantages and disadvantages. Because it is easy to use and reasonably priced, air conditioning is still one of the most common approaches. Using computational fluid dynamics (CFDs), Chen *et al*., [29] investigated the design of a parallel air-cooled BTMS with the goal of enhancing performance through the best possible choice of system characteristics. According to their research, raising the airflow rate lowers the maximum temperature but also dramatically raises power usage. Li *et al*., [30] conducted a more thorough analysis of air-cooling arrangements for lithium-ion battery packs. They found that cooling performance is improved by having more inlet and outlet manifolds. However, Chen *et al*., [31] observed that while active air cooling is a useful tool for lowering temperatures, it also causes significant temperature nonuniformity at low input velocities, which may have an adverse influence on battery cycle life.

Research on active cooling systems has also been done extensively, especially on air-cooled BTMS. Hou *et al*., [32] suggested an air-cooled BTMS design optimization method based on the field synergy equation. Optimizing structural factors and flow rate distribution greatly reduces temperature variations across battery packs. Optimization techniques are essential to increase the thermal efficiency of air-cooled systems. A study conducted in 2020 by Hakeem *et al*., [33] showed that forced convection cooling is effective. Their investigation into different air flow rates and current levels showed that increasing air flow significantly reduces maximum cell temperature and temperature differences within the battery pack. This empirical approach underscores the practical benefits of optimized air-cooling rates in enhancing BTMS performance. Figure 2 shows the basic/passive air-cooling technique for EV, cabin air ventilation, and active air-cooling heating.



(c)

Fig. 2. (a) Basic/passive air-cooling technique for EV, (b) cabin air ventilation, (c) active air-cooling heating [34]

Liquid cooling is another widely adopted technique due to its superior thermal conductivity compared to air. Al Qubeissi *et al*., [35] proposed using n-heptane as a dielectric hydrocarbon coolant. They demonstrated through numerical simulations that it offers significant improvements in system cost, weight, and temperature control compared to traditional coolants like 3M-Novec 7200. In their evaluation of several cooling techniques, Abdelkareem *et al*., [36] highlighted the potential of nanofluids to improve thermal management. According to their research, hybrid systems that combine PCMs or heat pipes with nanofluids may be able to provide more efficient and consistent temperatures. The work of Khan *et al*., [37] shows more developments in liquid cooling, as they presented a lightweight U-shaped liquid-cooled BTMS. A neural network-based regression model was used to enhance this system's performance, leading to notable drops in the maximum battery temperature and cooling plate weight. The effectiveness of this approach in preserving temperature uniformity and overall thermal safety demonstrated the potential of machine learning in BTMS design optimization. Liquid-cooling BTMS is continuously developing thanks to creative design advancements. Zhao *et al*., [38] emphasized developments in heat transfer jackets, liquid-phase-change material hybrid cooling systems, and coolant channel design. The limits of previous systems are addressed, and a holistic approach to battery thermal management is provided by these advances, which improve cooling efficiency and thermal performance. Basic liquid cooling technique for EV is shown is Figure 3.

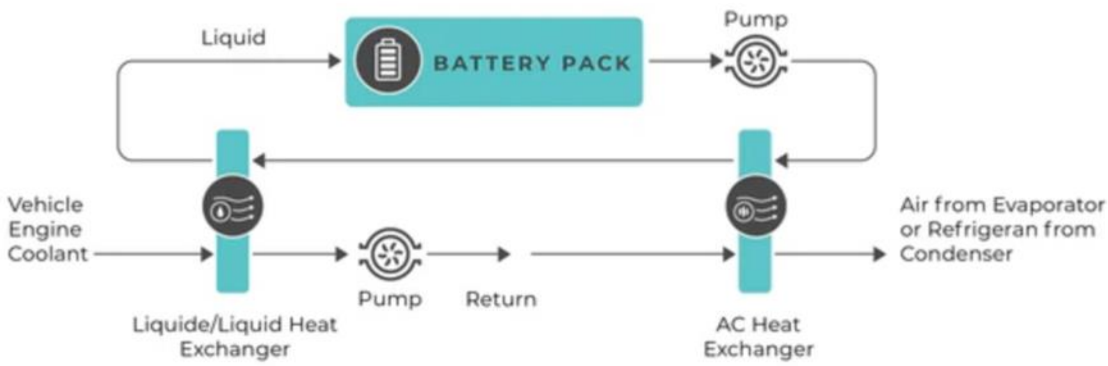


Fig. 3. Basic liquid cooling technique for EV [39]

Operating temperatures have a major impact on lithium-ion battery longevity, safety, and efficiency in electric cars. BTMS must be developed with high thermal loads in consideration. A novel strategy is the hybrid system, which combines forced air cooling with direct liquid cooling. Such a system, which combines forced air cooling with a jacket filled with liquid coolant surrounding the battery, was invented by Zhao *et al*., [38] in 2023. According to numerical simulations, the best cooling was obtained with a 5-mm gap between the cooling jacket and battery, a dual-pipeline liquid-cooling construction, and a parallel flow arrangement. The system's fire suppression capacity improves EV safety, and it demonstrated outstanding heat dissipation at a 4-C discharge rate.

The capacity of PCMs to absorb and release large amounts of thermal energy has drawn attention. A PCM-based internal cooling design for cylindrical lithium-ion batteries was studied by Shi *et al*., [40], who found that it offers a more even temperature distribution than external cooling techniques. In their extensive analysis of the advantages of PCM-based BTMSs, Zadehkabir *et al*., [41] highlighted two important benefits: their simplicity and high heat storage capacity. The process of choosing the right PCMs and integrating them into the current systems is still challenging, in any case. Systems for passive cooling are also essential to BTMS. The implementation of nano-enhanced phase change materials (NePCM) into passive cooling systems was examined by Bhutto *et al*., [42]. Because of their enhanced thermal conductivity, these materials are able to regulate the battery's operating temperature.

NePCMs with latent heats of 80–120 J/g and thermal conductivities of 1-2 W/(m·K) are recommended. Research demonstrated that these devices were effective in keeping battery surface temperatures below 50°C, proving that they can avoid thermal runaway and prolong battery life. Using PCM combined with metal foams and fins is another passive approach. Different fin forms were studied by Najafi Khaboshan *et al*., [43] in order to maximize cooling performance. Fins, metal foam, and PCM worked together to successfully lower battery surface temperatures and postpone PCM melting, resulting in a stable thermal environment even at high discharge rates. This technique emphasizes how crucial material choice and structural optimization are too passive cooling techniques. Figure 4 shows the basic phase change material for EV, before packed by PCM, after packed by PCM.

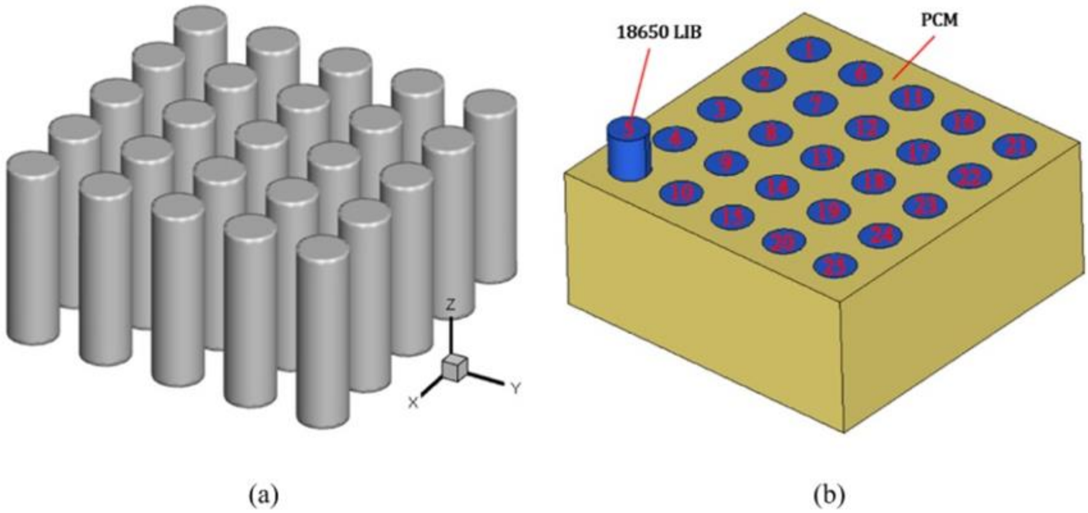


Fig. 4. Basic phase change material for EV; (a) before packed by PCM; (b) after packed by PCM [44]

Another promising technique for BTMS is heat pipes. A comprehensive study of heat pipes in BTMS was conducted by Bernagozzi *et al.*, [45], who highlighted the heat conductivity and passive functioning of these pipes. They observed that system adaptability and the usage of ecologically friendly operating fluids should be the primary topics of future study. In order to enhance the performance, Abdelkareem *et al.*, [36] also covered the use of heat pipes combined with other cooling techniques, such as nanofluids. Immersion cooling is an unconventional but very successful technique. In their evaluation of several heat pipe arrangements, Weragoda *et al.*, [46] noted that loop and pulsing heat pipes have the ability to maintain ideal cell temperatures. Before these devices can be promoted, however, issues, including performance under different heat loads and climatic circumstances, must be resolved. Figure 5 shows the basic heat pipe cooling method.

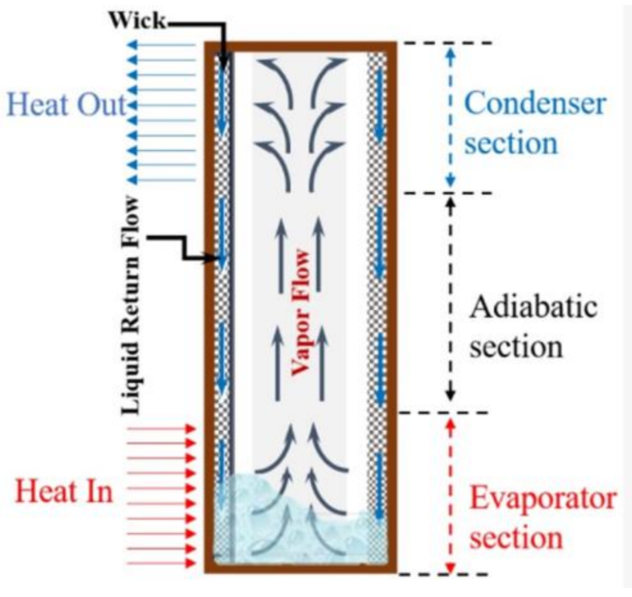


Fig. 5. Basic heat pipe cooling method [47]

A data-driven numerical model for immersion cooling of lithium-ion batteries was verified by Solai *et al.*, [48]. In comparison to air or liquid cooling techniques, their investigation showed that immersion cooling might significantly improve thermal management by keeping battery temperatures within ideal limits under a variety of operating situations. Even though this method works effectively, it needs to be properly designed to avoid contaminating the coolant and guarantee system stability. Novel approaches, such as the ones put out by Ramani *et al.*, [49] use Radio Frequncy Identification (RFID)-based devices to monitor and cool batteries in real-time. According to their research, EV efficiency and user experience may be improved by combining RFID with Internet of Things (IoT) modules for smart charging and temperature control. This strategy could help with issues with charging station accessibility, path planning, and heat control in sophisticated smart cities. Immersion cooling method is shown in Figure 6.

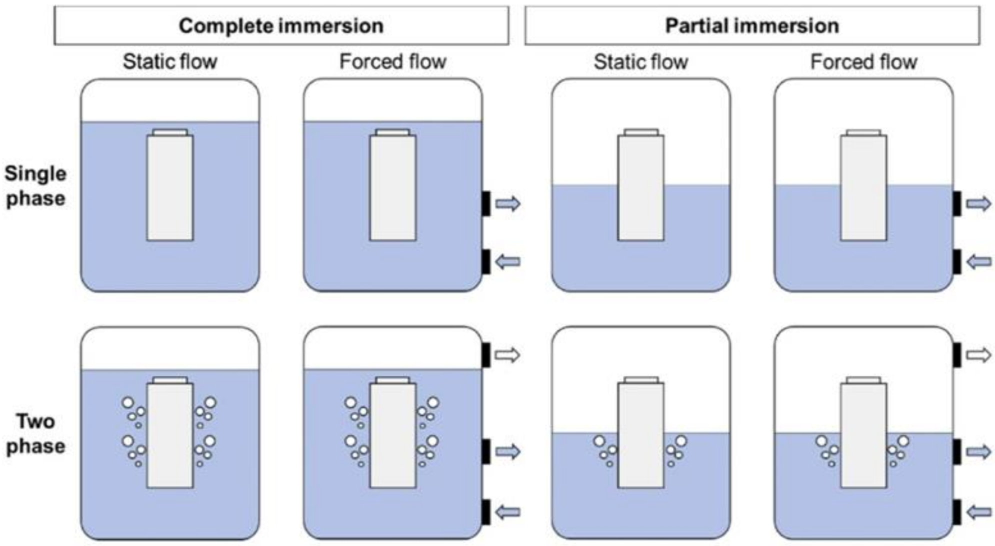


Fig. 6. Immersion cooling method [50]

In conclusion, a variety of cooling methods, ranging from hybrid systems combining liquid and air cooling, lightweight liquid-cooled systems, passive cooling with NePCM and metal foams, to optimized air-cooled and heat pipe-based systems, are being explored to enhance BTMS in EVs. These advancements collectively contribute to improving the safety, efficiency, and lifespan of EV batteries, addressing both thermal management challenges and future research directions. The ongoing research and development of BTMS for EVs encompass a range of cooling methods, each with specific benefits and limitations. Air cooling remains a cost-effective solution but struggles with temperature uniformity. Liquid cooling offers improved performance but at higher complexity and cost. PCMs and heat pipes provide efficient thermal management but require careful material selection and integration. Immersion cooling presents a highly effective alternative but faces practical implementation challenges. Future advancements are likely to involve hybrid systems and smart technologies to achieve optimal thermal management in EVs.

3. Material and methods

3.1 Identification

A few key steps in the systematic review process were used to select a large number of related research for this investigation. After selecting keywords, appropriate phrases are looked up using dictionaries, thesaurus, encyclopedias, and prior research. All relevant terms were selected after search strings for the databases Scopus and Web of Science (WoS) were created (see Table 1). In the first step of the systematic review procedure, 329 papers for the present study project were effectively pulled from both databases.

Table 1
The search strings

Scopus	TITLE-ABS-KEY (("Cooling Techniques" OR "cooling methods" OR "cooling approaches" OR "cooling systems") AND ("Battery Thermal Management" OR "Thermal Control system for battery" OR "battery heat management" OR "battery temperature regulation system") AND ("Electric Vehicle" OR "Electric Transport" OR ev)) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2023) OR LIMIT-TO (PUBYEAR, 2024)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j")) Date of Access: MAY 2024
WOS	("Cooling Techniques" OR "cooling methods" OR "cooling approaches" OR "cooling systems") AND ("Battery Thermal Management" OR "Thermal Control system for battery" OR "battery heat management" OR "battery temperature regulation system") AND ("Electric Vehicle" OR "Electric Transport" OR EV) (Topic) and 2022 or 2023 or 2024 (Publication Years) and 2022 or 2023 or 2024 (Publication Years) and Article (Document Types) and English (Languages) Date of Access: MAY 2024

3.2 Screening

During the screening phase, the collection of potentially relevant study items is evaluated for content that is consistent with the specified research topic or questions. One of the typical content-related criteria used in this phase is the selection of research topics based on the Present Cooling Method for BTMS in EV. The list of recovered documents has been updated to include all duplicate papers. Two stages of screening were carried out: 200 publications were evaluated in the second stage according to the different criteria for inclusion and exclusion of this inquiry, while 129 articles were removed in the first stage (see Table 2). The primary criterion was the research literature because it is the primary source of practical advice. This covers materials such as evaluations, meta-syntheses, meta-analyses, books, book series, chapters, and conference proceedings that were left out of the most current investigation. Moreover, the evaluation was limited to articles written in English and focused solely on the years 2022–2024. A total of 17 items were rejected due to duplication.

Table 2
The search selection criterion

Criterion	Inclusion	Exclusion
Language	English	Non-English
Time line	2022 – 2024	< 2021
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press

3.3 Eligibility

Once all inclusion and exclusion criteria have been applied, the final review sample is put together. The full list of research items included in this sample must be disclosed in order for readers to comprehend the basis for the study results reviewed in this review. There are 183 articles in the eligibility level, which is the third level. At this point, every article's title and important text were carefully evaluated to make sure it satisfied the inclusion requirements and related to the goals of the research project. As a result, 134 papers were removed from consideration because, based on actual facts, their titles and abstracts had no obvious impact on the goal of the study. In the end, 49 articles were chosen for assessment.

3.4 Data Abstraction and Analysis

This study used a comprehensive evaluation as one of the assessment processes to look at and synthesize a variety of research designs (quantitative, qualitative, and mixed methodologies). The goal of the competence research was to identify relevant subjects and subtopics. The phase of data collection was the first in the theme's development. Figure 7 shows how the authors meticulously went through a selection of 49 articles in search of assertions or details pertaining to the topics of this investigation. Subsequently, the authors evaluated noteworthy new research on the subject of current cooling methods for EV BTMS. The research findings and the methodologies used in each study are being analyzed. The author then collaborated with the other co-authors to develop themes derived from the study's background data. A log was kept during the data analysis process to document observations, viewpoints, difficulties, and other concepts pertaining to the analysis of the data. Finally, the authors examined the results to see whether there was any contradiction in the theme design process. It is significant to observe that the authors discuss any disagreements they may have about one another's opinions. The authors also compared their results to resolve any discrepancies in the theme-generating process. It should be mentioned that the authors address any inconsistencies about the ideas that might have risen up. Finally, the established motifs were modified to ensure uniformity. Two experts, one focused on heat transfer and the other on the automotive sector, conducted the tests to confirm the veracity of the challenges. The expert review process validated the significance, sufficiency, and clarity of each sub-theme by proving domain validity. The author has made optional changes based on advice from experts and ideas.

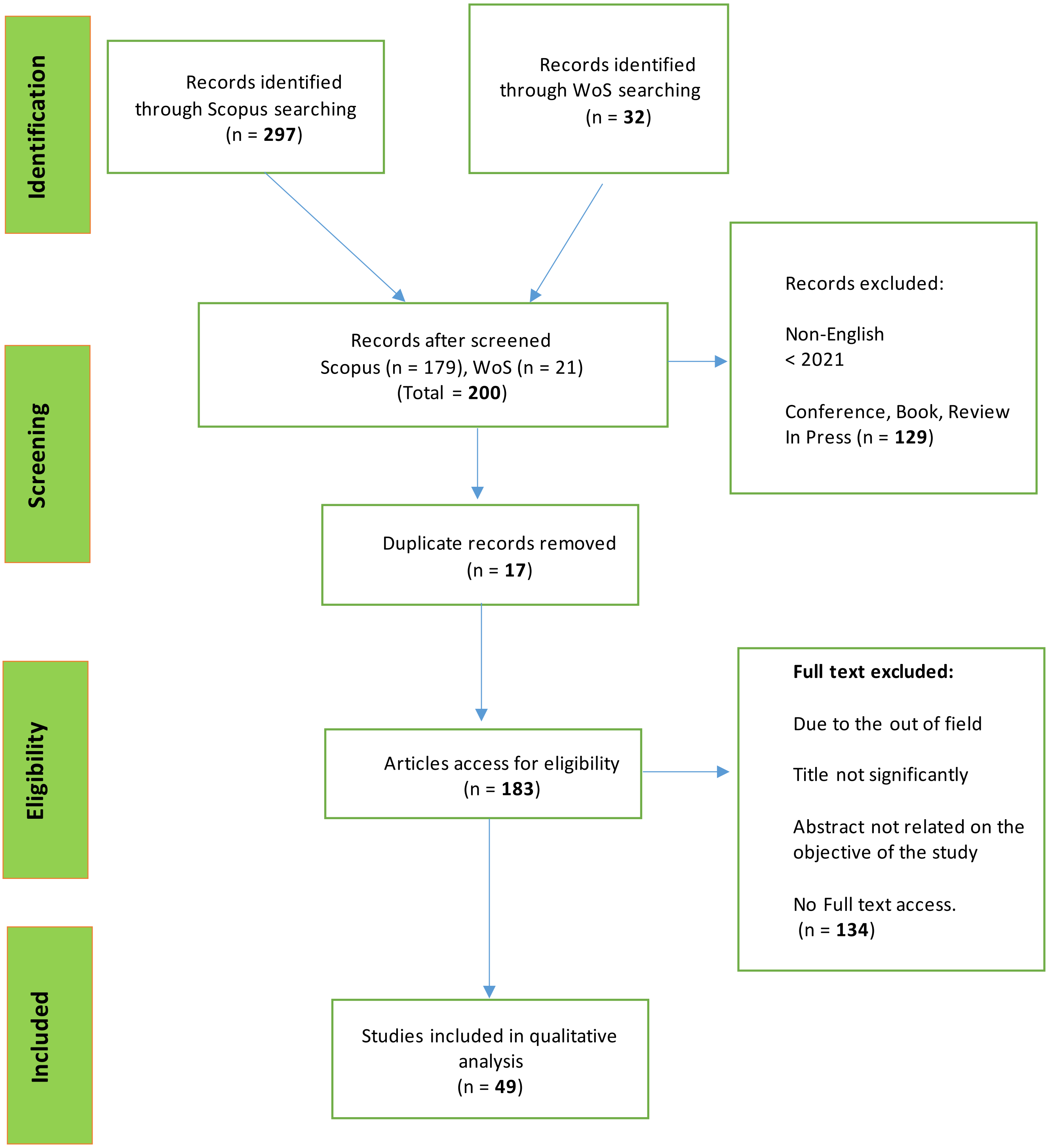


Fig. 7. Flow diagram of the proposed searching study [51]

4. Results and Findings

BTMS in EVs increasingly employ air-based cooling techniques because of these systems' low cost, straightforward design, excellent dependability, and few maintenance needs. Maintaining a consistent temperature distribution throughout the battery pack while preserving energy efficiency is the biggest challenge with air cooling. In order to improve heat transfer, lessen temperature gradients, and optimize airflow patterns, air-cooled BTMS performance has been studied through a variety of creative design alterations. These studies discuss different aspects of air-based cooling methods for battery systems, providing insights into the methodologies used, findings, and potential future research directions. Research shows innovative designs and optimization techniques that improve thermal performance and energy efficiency.

Maintaining peak performance and prolonging battery life in hybrid and EVs depends on effective thermal control of the battery systems. Overheating while in use can cause safety problems, deterioration in battery performance, and shorter battery life. Since liquid cooling techniques can dissipate heat more effectively than air cooling, they have drawn more attention. The goals, approaches, conclusions, and potential further study directions of many studies on liquid-based cooling techniques for thermal management systems for batteries are the main topics of this thorough examination. Hybrid cooling strategies, which integrate several approaches, including cooling by liquids, cooling by air, and PCMs, are also essential for improving the longevity, safety, and efficiency of lithium-ion batteries—particularly in EVs. The use of nanofluids in cooling techniques is also covered in this paper since they provide significant enhancements in heat transfer and thermal conductivity. While this is going on, heat pipe cooling techniques have become a prominent way to control the thermal performance of battery systems because of how well heat pipes carry heat.

Table 3
The research article's findings based on the proposed searching criterion

No	Author's Name and Year	Objectives	Methodologies	Findings	Conclusion & Future Research
AIR BASED COOLING					
1	Zhao, Gang *et al.,* 2022 [52]	To maximize the design of an EV air-cooling BTMS with several inlets and outlets.	Design optimization, performance evaluation	The finest temperature consistency and lowest energy consumption were demonstrated by the symmetrical double inlets/outlet configuration (Design 4).	Future research could explore further optimization of inlet/outlet configurations and examine performance under various operating conditions.
2	Zhao, Gang *et al*., 2023 [53]	To use a novel vortex adjustment design to improve the performance of an air-cooling BTMS.	Vortex generating columns, aerodynamic and thermodynamic analysis	Design 1 with T-shape vortex generators improved cooling performance at both low and high airflow rates with minimal energy increase.	Additional studies should investigate other vortex generator designs and their impact on different battery pack configurations.
3	Moosavi, Amin *et al*., 2023 [54]	To evaluate how large-scale air-cooled BTMS's thermal performance is affected by cell spacing.	Novel modelling approach, sub-models (analytical and numerical)	The maximum temperature within cells increased with larger pitch ratios, while temperature uniformity varied non-monotonically.	Further research could refine the modeling approach and explore different cell arrangements to optimize thermal management.
4	Shen, Xueyang *et al*., 2022 [55]	To investigate the air-cooled, redesigned Z-shaped BTMS for NEVs' thermal behavior.	Thermal analysis, non-vertical flow channel design	In comparison to the conventional design, the improved Z-shaped design greatly decreased the maximum temperature and temperature differential.	Future work could investigate other structural modifications and their effects on heat exchange rates and cooling efficiency.
5	Ye, Jiedong *et al*., 2024 [56]	To use a vortex generator to improve heat transmission in a BTMS.	Numerical investigation, orthogonal experimental design, fuzzy grey relational analysis	Optimal vortex generator positioning and design reduced temperature difference and maximum temperature significantly.	Further optimization of vortex generator parameters and exploration of other passive cooling enhancements are recommended.
LIQUID BASE COOLING					
6	Rammohan *et al*., (2022) [57]	To evaluate a liquid-cooled battery module's thermal performance at various intake velocities and cooling media.	Three-dimensional CFDs simulation	Optimal coolants are identified at various velocities, assessing minimum, average, and maximum temperatures.	Future research could explore different cooling mediums and configurations to enhance performance further.
7	Li *et al*., (2022) [58]	To analyse how cooling plate arrangement and channel design affect a battery	Numerical modeling and analysis; Z-score method	Better cooling performance is demonstrated by the design that places two cooling plates between one battery module. Under NEDC	Future research should focus on optimizing channel design and layout for various driving conditions and exploring

		module's ability to dissipate heat.		circumstances, cooling plates with many small flow channels operate best at particular inlet flow rates.	alternative coolant materials to further enhance cooling efficiency.
8	Xu *et al*., (2022) [59]	To increase battery energy density in high-density prismatic packs of lithium-ion batteries using a particular thermal management architecture.	Examination of an F2-type liquid system with cooling through experimentation using a M-mode configuration	The M mode of the F2-type liquid system of cooling demonstrated improved heat transfer performance and cooling efficiency.	Further optimization of inlet temperatures and flow rates under various conditions could be explored.
9	Feng *et al*., (2024) [60]	To select an optimal liquid cooling BTMS scheme based on system performance weights using the entropy weight method.	Evaluation using entropy weight method and cyclic testing conditions (WLTC and US06)	The serpentine flow channel with an aluminium cooling plate at 0.5 m/s inlet velocity was optimal.	Future research might examine the long-term effects on the system performance of various cooling plate materials and flow rates.
10	Vikram *et al*., (2022) [61]	To examine how Li-ion battery packs behave thermally while undergoing actual drive cycles with different coolants.	Numerical simulation with the FTP-75 and Indian drive cycles taken into effect	The best mixtures for temperature distribution and energy consumption were the water-propylene glycol combination at 25% concentration and the water-ethylene glycol mixture at 50% concentration.	Exploring the impact of varying ambient temperatures and additional coolant mixtures could be beneficial.
11	Chavan *et al*., (2023) [62]	To evaluate the efficacy of various cooling fluids and fluid flow routes in BTMS for EVs.	Numerical modelling of various fluid flow characteristics and cooling schemes	A curved channel filled with liquid cooling fluid showed the best rate of heat transfer.	Future research should focus on developing new channel designs and investigating their scalability for larger battery packs.
HYBRID COOLING					
12	Luyao Zhao *et al*., 2023 [38]	Introduce a new hybrid BTMS for lithium-ion battery modules that combines forced air cooling with direct liquid cooling.	Numerical simulations to analyse gap spacing, cooling pipelines, liquid flow rate, and fan position	The best configuration is a 5-mm spacing, double pipeline, and horizontal parallel flow. Optimum liquid flow rate: 0.002 kg/s, air flow rate: < 0.4 m/s. Effective at 4-C discharge rate.	High cooling efficiency for high-rate operations; future research could focus on optimizing energy efficiency further and exploring fire suppression benefits of liquid cooling.
13	Shiji Xin *et al*., 2023 [63]	Deliver a cylindrical lithium-ion battery pack, a hybrid BTMS that combines liquid and air cooling.	Three-dimensional simulation model analyzing HCBs, flow rate, and air-cooling effects	0.002 kg/s flow rate, 6 mm cooling channel diameter, and 3 HCBs are optimum values. The addition of air-cooling considerably reduces Tmax and ΔT.	Achieves a balance of cooling performance, power consumption, and weight; future research could explore intermittent air cooling to reduce power consumption further.

14	Isares D *et al.*, 2023 [64]	Improve the air-cooling system's cooling performance for EV battery modules by integrating liquid spray technology.	Three-dimensional transient heat transfer model in ANSYS Fluent	An optimized system reduces temperature nonuniformity and maximum temperature by approximately 4°C and 6°C, respectively.	Provides valuable design insights for spray-assisted cooling systems; future research could refine nozzle placement and liquid spray parameters for further optimization.
15	Jiedong Ye *et al.*, 2023 [65]	Examine a hybrid thermal control system for an 18,650-battery pack that uses both liquid and air cooling.	CFDs model using ANSYS SCDM and Fluent	The composite system reduces temperature difference to 3.73 K, the highest temperature to 317.38 K, and entropy production.	Improves cooling performance and reduces entropy production; future research could investigate different discharge rates and environmental conditions.
16	Sun J. *et al.*, 2023 [66]	Explain liquid cooling and pack-level BTMS for EV batteries using PCMs.	Enthalpy-porosity model for PCM, dynamic electro-thermal coupled model, along with k-ε model for coolant flow	PCM with 10% expanded graphite in paraffin wax works well; maximum temperature is decreased by increasing the mass flow rate or lowering flow temperature.	Effective for high-temperature conditions, future research could focus on optimizing PCM composition and flow rate for different battery configurations.
17	Hekmat S. *et al.*, 2022 [67]	For battery modules to have a consistent temperature distribution suggested a hybrid BTMS with PCM and liquid cooling channels and temperature distribution in battery modules	Numerical simulations under different discharge rates and coolant flow rates	A counter-flow cooling hybrid BTMS may achieve a temperature difference of less than 0.7°C.	Significantly improves temperature uniformity; future research could explore different PCM materials and configurations.
18	Xu C. *et al.*, 2024 [68]	Present a new thermal management approach combining CPCM and liquid cooling for large-format pouch batteries	Optimized hybrid cooling model, benchmark studies on inlet position, flow rate, and channel distribution	BTMS with CPCM-3 maintains a max temperature of 41.15°C and a temperature difference of 4.89°C.	Effective under high-temperature conditions, future research could optimize liquid flow rate and explore other CPCM combinations.
19	Khan A. *et al.*, 2024 [69]	Examine how different cooling techniques affect a Li-ion battery pack when it is being charged and discharged.	Investigating natural cooling, heat transfer fluid cooling, eutectic PCM cooling, and hybrid cooling via experimentation	When compared to natural air cooling, hybrid cooling lowers the maximum temperature by 46.18%.	Demonstrates significant cooling efficiency; future research could explore other eutectic PCM combinations and scale for larger battery packs.
	PHASE CHANGE MATERIAL				

20	Yang J. *et al*., (2023) [70]	For optimizing the thermal management system of PCM-fin structure Li-ion batteries under mechanical vibrating situations.	Comparative study, Experimental analysis	A decrease of 0.55 K in LIB temperature and 5.67% in BTMS weight are the results of mechanical vibration's effect on ideal fin construction parameters.	Mechanical vibrations are crucial for BTMS design, promoting lightweight EV development.
21	Sudhakaran S. *et al*., (2023) [71]	To examine how PCM cooling performance is affected by material, thickness, additive proportion, and heat transfer coefficient.	Numerical simulation using ANSYS Fluent, Taguchi analysis, ANOVA	The smallest cell temperature that can be attained using capric acid is 35.4%. The main factors that affect cooling are the PCM material, thickness, heat transfer coefficient, and additive percentage.	Further optimization of PCM materials and configurations for improved BTMS efficiency.
22	Alami A.H. *et al*., (2022) [72]	To give a summary of the various PCM kinds and how they are used in BTMS for EVs.	Literature review	PCMs show high thermal management performance, and hybrid systems (PCM with air/liquid, heat pipes, nanoparticles) are effective.	Hybrid PCM-based BTMS is promising, with future research needed on overcoming limitations and improving thermal performance.
23	Nagmule S.A. *et al*., (2023) [73]	To investigate passive cooling techniques using PCM and heat sink for battery thermal management.	Experimental analysis with mock-up cells	PCM extended the operating temperature limit time by 100.8% at 10W, and heat sink integration improved cooling.	Insights into heat dissipation can guide future BTMS designs for enhanced thermal safety.
24	Mohankumar S. *et al*., (2022) [74]	To investigate the thermal behaviours of PCM-equipped battery packs at various discharge rates and air flow scenarios	Computational analysis using ANSYS	The maximum temperature of the battery pack was reduced with PCM; adding expanded graphite further reduced the temperature.	Future research could focus on optimizing PCM thickness and materials for better BTMS efficiency.
25	Rajan J.T. *et al*., (2022) [75]	Examine the use of 1-tetradecanol as a PCM in BTMS for EVs' LiFePO4 batteries.	Computational modelling using ANSYS Fluent	1-Tetradecanol PCM shows potential for lightweight, cost-effective BTMS with good thermal performance, limiting battery temperature within acceptable ranges.	Future research should focus on improving PCM thermal conductivity and integrating conductivity-enhancing materials to optimize performance.
26	Yang W. *et al*., (2023) [76]	Create a composite PCM using halloysite nanotubes that are highly thermally conductive and leak-proof for BTMS.	Physical mixing technology and in situ chemical reduction	Composite PCM with PEG/EG/HNT@AP shows enhanced thermal conductivity and stability, effectively managing battery temperature under high discharge rates.	Future research should explore further enhancements in thermal conductivity and investigate long-term performance and stability in real-world conditions.
27	Wang Z. *et al*., (2024) [77]	Create an inorganic composite PCM that is flame-retardant and has better	Experimental study using sodium acetate trihydrate matrix and polyurethane coating	Composite PCM exhibited high thermal conductivity and latent heat,	Future studies should aim to optimize the PCM composition for better cycle stability and

		thermal conductivity for the BTMS.		maintaining battery temperature under extreme conditions.	investigate its integration into commercial BTMS.
28	Kök C. *et al.*, (2023) [78]	Examine the thermal behaviours of Li-ion batteries of the pouch type using various cooling techniques.	Numerical simulations using the MSMD battery model	Liquid cooling outperformed air and PCM cooling, with the PCM showing moderate improvement in thermal distribution.	Future research should compare various PCM formulations and configurations to enhance cooling efficiency and uniformity.
29	Behi H. *et al.*, (2022) [79]	Optimize BTMS for cylindrical Li-ion battery module utilizing PCM and PCM-graphite.	Experimental study and numerical simulations with COMSOL Multiphysics	PCM-graphite significantly reduced temperature and improved uniformity compared to PCM alone, enhancing thermal management.	Future studies should focus on scaling the PCM-graphite system for larger battery modules and exploring its long-term performance in operational environments.
NANOFLUID COOLING METHOD					
30	Selimefendigil F *et al.,* (2024) [80]	To provide a hybrid nanofluid and corrugated cooling channel cooling technology for prismatic Li-ion batteries.	Method using finite elements and hybrid nanofluid at different solid volume percentages	The largest temperature drop was linked to higher cooling channel counts and solid volume percentages.	Future research could explore optimizing the groove design and other geometrical modifications to further enhance cooling efficiency.
31	Soleymani P. *et al.*, (2023) [81]	To improve BTMS in both steady-state and transient scenarios utilizing CuO and Al2O3 nanofluids.	k-ε turbulence model, transient analysis	Nanofluids improved cooling efficiency, with Al_2O_3 showing better performance.	Future studies could focus on long-term performance and the impact of different nanofluid formulations under varying operational conditions.
32	Kumar K. *et al.*, (2024) [82]	To assess new micro-channeled BTMS designs using hybrid nanofluids for cylindrical batteries.	3D numerical simulation, two-phase mixture model	Improved temperature uniformity and heat transfer with increased nanoparticle concentration.	Further research could investigate alternative nanofluids and their long-term stability and impact on battery life.
33	Khalili H. *et al.*, (2022) [83]	To mitigate battery degradation using a nanofluid thermoelectric cooler-based BTMS.	Thermoelectric cooling elements, parametric analysis	Reduced battery degradation and energy consumption, with optimal heat transfer coefficients identified.	Future research should look into optimizing thermoelectric elements and exploring new nanofluid compositions.
34	Kumar K. *et al.*, (2024) [84]	To analyze the effect of nanoparticle shape on BTMS performance using serpentine microchannels.	Multi-Scale Multi-Domain framework	Different nanoparticle shapes significantly impacted cooling performance and pumping power.	Future work should focus on optimizing nanoparticle shapes and concentrations to balance thermal performance and energy efficiency.
35	Mustafa J. *et al.*, (2022) [85]	To examine Li-ion battery thermal management using PCMs and nanofluid combined cooling.	Finite element method	Enhanced cooling with hybrid nanofluid-PCM system, better heat absorption.	Future studies should explore different PCMs and nanofluid combinations for optimized performance.

36	Guo Z. *et al*., (2023) [86]	To design and optimize BTMS considering battery aging and nanofluids.	Electrochemical and heat transfer modelling	Effective cooling in early cycles diminished performance over time due to SEI formation.	Future research should focus on mitigating SEI effects and improving long-term cooling efficiency.
37	Thakur S.S. *et al*., (2024) [87]	To develop a lightweight BTMS with enhanced contact area using heat-conducting elements and nanofluids.	Numerical analysis with varying contact angles and heights	Significant temperature and weight reduction, enhanced heat transfer with Cu-water nanofluid.	Future work could focus on optimizing heat-conducting element designs and exploring different nanofluids.
38	Alnaqi A.A. (2022) [88]	To examine the non-Newtonian nanofluids' pressure drop and heat transfer in BTMS.	Finite element technique, COMSOL software	Enhanced thermal performance with non-Newtonian nanofluids, reduced thermal resistance.	Future studies should investigate different non-Newtonian fluids and their long-term effects on battery performance.
39	Rana S. *et al*., (2024) [89]	To experimentally investigate BTMS using MWCNT-based nanofluids.	Experimental analysis	Improved thermal management and uniform temperature distribution with MWCNT nanofluids.	Future research should consider long-term effects and different nanomaterial compositions for optimized performance.
HEAT PIPE COOLING METHOD					
40	Bernagozzi M. *et al*., (2024) [90]	To examine how a BTMS with a Loop Heat Pipe (LHP) functions at various outside temperatures.	Experimental tests in environmental thermal chamber	LHP effectively worked under various temperatures, reduced heating delay, and improved cooling.	Further optimization of LHP for better performance in extreme conditions.
41	Han U. *et al*., (2023) [91]	To assess and enhance the hybrid fin structure for BTMS's HP-assisted performance in extremely hot environments.	Artificial Neural Network, Finite Difference Method, Multivariate Optimization	HF-BTMS showed significant temperature reduction and improved temperature deviation.	Explore other critical variables for further performance enhancement.
42	Han U. *et al*., (2023) [92]	To look at the BTMS's thermal performance under fast charging circumstances with an HP-assisted hybrid fin construction.	Utilizing varying coolant flow rates and intake temperatures in an experimental study	BTMS maintained a maximum temperature below 45°C and reduced thermal resistance significantly.	Investigate long-term performance and scalability for larger battery modules.
43	Yang J. *et al.*, (2024) [93]	To investigate battery side cooling technique with a flat confined loop heat pipe (FCLHP).	Numerical simulation using the VOF method and Lee phase-change model	FCLHP exhibited better temperature uniformity and lower thermal resistance.	Develop comparative studies with other cooling methods and optimize FCLHP design.
44	Oh I.-T. *et al*., (2023) [47]	To introduce a BTMS combining immersion cooling with heat pipes using NovecTM 649.	1-D modeling, AMESim simulations, Experimental validation	Effective temperature maintenance within the 27-34°C range, reduced thermal resistance.	Expand testing to higher heat inputs and explore alternative dielectric fluids.

45	Abd H.M. *et al*., (2024) [94]	To evaluate several BTMS models, such as a recently developed hybrid flat heat pipe that incorporates PCM.	Analysis of experiments conducted at different air speeds and discharge rates	The new model effectively reduced the maximum operating temperature and temperature difference.	Further refine the model for better performance at higher discharge rates.
46	Sharma D.K. *et al*., (2023) [95]	To evaluate the PCM-HP hybrid BTMS fin designs' thermal performance under continuous cycling.	2D computational model, Experimental validation	Optimal fin design reduced maximum battery temperature significantly.	Investigate long-term durability and the effects of varied ambient conditions.
47	Wang J. *et al*., (2024) [96]	For prismatic lithium-ion batteries, to optimize a new BTMS that combines a composite fin and heat pipe.	Model comparison, Optimization analysis	HPCF displayed superior thermal performance and maintained desired temperature ranges.	Implement liquid cooling strategies for extreme conditions and enhance energy efficiency.
48	Gao C. *et al*., (2024) [97]	Phase-change material and heat pipes together to enhance BTMS performance.	Numerical comparative analysis	PCM + HP system significantly decreased maximum temperature and improved temperature uniformity.	Extend studies to different battery configurations and optimize PCM-HP integration.
49	Hongkun L. *et al*., (2024) [98]	To improve heat transmission in a battery liquid cooling system using an oscillating heat pipe in the shape of a ⊥ under pulsating flow.	Experimental analysis of pulsating flow parameters	The new system improved heat dissipation and temperature uniformity.	Explore different pulsating flow parameters and integrate them with other cooling technologies.

5. Discussion and Conclusion

Due to its simple design and low maintenance needs, air cooling is an economically viable solution for BTMS. Recent advancements have focused on optimizing design and incorporating innovative modifications to enhance thermal performance and temperature uniformity. Innovations like multiple inlets and outlets, as opposed to traditional single designs, significantly improve temperature uniformity and reduce energy consumption, with the symmetrical double inlets/outlets design notably reducing maximum temperature and differences, particularly during mild discharging operations. Aerodynamic improvements include columns that form a T-shaped vortex and change aerodynamic patterns, lower maximum temperatures, and changes in airflow rates while increasing the coefficient of heat transfer with the lowest possible amount of energy. The optimum temperature within battery cells is connected with the longitudinal and transverse pitch ratios, suggesting that balanced spacing improves thermal performance. This means that battery cell spacing and arrangement must be optimized. A non-vertical Z-shaped design, for example, drastically reduces the maximum temperature and enhances temperature uniformity while speeding up heat exchange. With proper position, vortex generators minimize temperature differences and maximum temperatures while improving the transfer of heat even further. The combined findings of these research emphasize the significance of attentive design and optimization in creating efficient air-cooled BTMS, promising improved EV battery longevity, safety, and efficiency.

Thermal management is crucial for enhancing the safety, longevity, and performance of lithium-ion batteries in EVs. Liquid-based cooling systems have gained popularity because of their exceptional heat dissipation capabilities. Rammohan *et al.,* [57] carried out a thorough investigation to look at the thermal performance of liquid-cooled battery modules using three-dimensional CFD simulations. Their investigation aimed to determine the lowest, average, and maximum battery cell temperatures at a 2C discharge rate through the comparison of different cooling mediums and intake velocities. It has been thoroughly investigated how cooling plate designs affect battery temperature management. Li *et al.,* [58]examined a variety of cooling plate channel configurations, such as single, S-shaped, and many microscopic channels. The cooling plates with several small channels worked best under New European Driving Cycle (NEDC) conditions, with an inlet flow rate ranging from 7.817 × 10−4 kg s^{-1} to 0.0105 kg s^{-1}, according to their computational studies.

This configuration demonstrates the importance of channel design in liquid cooling systems as it improves heat dissipation and temperature management. In 2022, Xu *et al.*, [59] presented a new method to increase the energy density of lithium-ion batteries by using an F2-type liquid cooling system with an M-mode cooling plate array. They found that the F2-type, compared to other variants, has better heat transfer and cooling performance. The study found that an intake temperature of about 18.75°C and a certain flow rate are required to maintain the ideal battery temperature throughout the charge-discharge cycle, which shows how important it is to properly position the cooling plate and flow rate to control heat. For the optimization of liquid-based cooling techniques, Feng *et al.,* [60] evaluated 36 different BTMS schemes using the entropy weight method (EWM). Cooling plate material, inlet flow velocity, and flow channel layout were all taken into account in their study.

An aluminium plate serpentine flow channel layout with an inlet flow velocity of 0.5 m·s−1 shows the best cooling efficiency, energy consumption and material cost, according to the research. The results show that conducting a comprehensive evaluation of various criteria is important to select the best BTMS. Vikram *et al.*, [61] have investigated the performance of liquid-based BTMS under the Federal Test Procedure Drive Cycle (FTP-75) and the Indian Drive Cycle. This study was then extended to real-world driving situations. They combined various coolant combinations, including water, water-ethylene glycol and water-propylene glycol, to show that a mixture of 25% propylene glycol and 50% ethylene glycol consumes a lot of energy and spreads the temperature well. The focus of this study is the effect of drive cycle and room temperature on BTMS performance. Finally, Chavan *et al*., [62] using numerical simulations to evaluate various fluid flow channel topologies. These topologies include rectangular, open and curved channels.

Curved channels filled with cooling liquid demonstrate optimal heat transfer rates and temperature management, increasing the reliability and safety of battery operation. This shows how important the channel shape is to improve the thermal efficiency of liquid-cooled BTMS. Therefore, the use of a liquid-based cooling system for BTMS is a good choice because it allows the regulation of battery temperature and improves the performance of electric cars. Coolant type, flow rate, channel layout and cooling plate design greatly affect the efficiency of this system. Studies by Rammohan *et al.,* [57], Li *et al.,* [58], Xu *et al.,* [59], Feng *et al.,* [60], Vikram *et al.,* [61] and Chavan *et al.,* [62] shows that the development of a more efficient and sustainable BTMS is necessary.

Hybrid mixed cooling strategies for lithium-ion batteries have attracted great attention in recent research for better thermal control and improved battery performance. In their investigation of a new thermal management system that uses forced air cooling and direct liquid cooling, Zhao *et al*., [38] emphasizes the importance of optimizing flow rates, cooling pipeline structures, and gap spacing for cooling. The results of the study found that the twin pipe architecture with horizontal parallel flow and 5 mm gap reduces battery temperature and energy consumption at high discharge rates. Furthermore, Xin *et al*. [63] shows that the heat conducting block (HCB) works well to cool the air, balancing power consumption and cooling effectiveness. Studies have found that thermal management systems that use air and liquid cooling can reduce both the maximum temperature and the temperature difference. In 2023, Dhuchakallaya and Saechan [64] introduced a new method for cooling battery modules. This technique lowers both the maximum temperature and temperature non-uniformity by using a non-conductive liquid spray combining forced air and hydrofluoroether. They found that maintaining the same mass flow rate and changing the nozzle location was necessary to improve cooling efficiency, which is an important part of preventing EVs from escaping heat. By combining air and liquid cooling, Ye *et al*., [65] significantly reducing the temperature range of the battery pack, improving overall thermal management performance.

The effect of heat at different liquid and air flow rates was also studied using a CFD model. Additionally, studies have looked at the possibility of providing a uniform temperature distribution when phase change materials (PCM) are incorporated into thermal management systems. Hekmat *et al*., [67] showed how a hybrid BTMS using PCM and liquid cooling channels could be used to provide a highly even temperature distribution and reduce temperature fluctuations between cells to less than 0.7°C. This configuration ensures the safety and endurance of the battery module and performs particularly well at high discharge rates. In addition, Sun *et al*., [66] shows how such a system can improve temperature uniformity and significantly reduce maximum temperatures by combining PCM with liquid cooling at the pack level. Their findings improve the performance of BTMS under various operating conditions and support the extended effectiveness of graphite as a PCM component in paraffin wax. Khan *et al*., [69] conducted additional experimental studies on a hybrid cooling system using a heat transfer fluid and eutectic PCM. The results show a significant temperature drop compared to natural air cooling. This technique shows how significantly reducing the maximum surface temperature and temperature gradient can improve battery performance and safety. In general, the hybrid combined cooling method solves the thermal management issue of lithium-ion batteries by combining various cooling techniques, such as forced air cooling, direct liquid cooling and PCM cooling. When it comes to the electric car market and other applications that rely on high-performance battery systems, this combination of strategies improves cooling, temperature stability and battery life.

More creative configurations and designs, such as combining multiple cooling methods for more effective heat removal and more uniform temperature distribution, should be the subject of future research. Research should also focus on the use of new materials that can improve cooling performance as well as the creation of innovative models that can more accurately predict the performance of cooling systems under various operating conditions. Additionally, the integration of advanced modelling techniques and experimental validation will enable more creative and effective BTMS designs. To improve the reliability and effectiveness of air-cooled BTMS in electric vehicles, research should continue to examine new configurations and active cooling mechanisms. Finding new materials, optimizing the composition of nanofluids, and addressing long-term performance and stability under various operating conditions will be important. Finally, efficiency and safety will be improved by optimizing heat pipe systems for various battery configurations, improving long-term performance, and exploring new materials and designs.

Declaration Of Competing Interest
The authors declare that the work reported in this study was not affected by any conflicting financial interests or personal connections.

Data Availability
No data was used for the research described in this article.

Acknowledgement
The authors extend their sincere gratitude to the Ministry of Higher Education (MoHE), Malaysia through the Fundamental Research Grant Scheme: FRGS/1/2024/TK10/UMP/02/15 and Universiti Malaysia Pahang Al-Sultan Abdullah (RDU240117) for their invaluable financial support provided. This support has been instrumental in facilitating the successful execution of this research project. The support by School of Automotive Engineering from Jiangxi Polytechnic University, China was also acknowledged and appreciated.

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