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Comprehensive Evaluation of Parametric Analysis of Battery Thermal Management Systems in Electric Vehicles

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Abstract

Electric vehicles (EVs) employing lithium-ion battery can be regarded as a sustainable mode of transportation with reduced ecological impact due to their minimal to negligible GHG gas emissions and diminished noise emissions. Employment of an effective battery thermal management system in EVs is of utmost importance as li-ion batteries tend to heat up during its charging and discharging process, which results in reduced battery performance and shorter battery lifespan, sometimes, even leading to thermal runaway and vehicle fire. The efficiency of battery thermal management systems depends on various parameters of the coolant and the technology implemented. This paper evaluated the available research on parametric analysis of thermal management technologies, where certain parameters are varied to get an optimum parametric combination for enhanced performance of the system. It was observed that hybrid thermal management systems demonstrate better performance than conventional ones. Besides, for various battery thermal management modules, different parameters, when selected as independent variables, lay a significant impact on the performance of the systems. Furthermore, a statistical analysis has been conducted on the available works. Lastly, a summary has been prepared reflecting on the important parameters obtained for improved BTMS performance.

Keywords: electric vehicle, li-ion battery, parametric analysis, battery thermal management system.

1. Introduction

As the global community is advancing towards environment-friendly and sustainable energy consumptions, the E-mobility approach strives to expedite the advances by integrating electric vehicles (EVs) in the consumption process, replacing traditional vehicles which depend on conventional energy sources. At this point, Li-ion batteries predominate the market as secondary energy storage devices for EVs due to their excellent characteristics such as extended lifespan, effective energy performance, non-existent memory impact and optimal energy and power density[1]. Research findings indicated that the optimal temperature range for effective performance of Li-ion battery cells lies between 0°C and 40°C. However, over the course of charging/discharging, Li-ion batteries tend to produce a substantial amount of heat which, in conjunction with space limitations and prolonged usage, increases the battery temperature. This decreases battery performance and diminishes its durability. Further studies have demonstrated that as the increasing temperature of a single battery surpasses its recommended working temperature, it results in thermal runaway, which may propagate through the entire battery pack inside an EV, leading to vehicle fire. On the other hand, low-temperature charging and discharging of Li-ion batteries can lead to lithium deposition on anode surfaces, which may result in shorter battery lifespan, diminished battery capacity and deterioration in performance[2].These analyses reflect the significance of an effective battery thermal management system (BTMS) to dissipate the accumulated thermal energy, which ensures the proper functioning of the battery within a suitable temperature range[3][4]. Existing BTMSs are categorized based on various factors. A few authors have classified battery thermal management systems on the basis of energy usage pattern of the system into active and passive cooling systems [5]. Classification based on the heat transfer medium used in the system may be considered as the most common approach, which classifies BTMSs into different categories such as those utilizing air, liquid coolants and PCMs [5]. Alternative strategies for the thermal management system of batteries include the utilization of heat pipes and TECs. State-of-the-art technologies involve the integration of multiple battery thermal management systems into hybrid/integrated models.

The performance of existing battery thermal management systems can be improved by adjusting key parameters or independent variables. Based on the BTMS category, the parameters vary, for example, suitable electrode materials for batteries, type of heat transfer agent employed or alterations in overall configuration of the system can bring about significant thermal and cooling performance enhancement of the system in consideration.

However, optimizing these variables for improved efficiency of the system often involves inherent trade-offs associated with design complexity, weight, power consumption, and overall economy of the system. Through systematic alteration of input parameters within a defined range, parametric analysis, alongside investigating the resulting changes in the system effectiveness, provides a framework for understanding these trade-offs. This analytical approach facilitates in selection of optimal combinations of parameters for the best plausible cooling efficiency of the system, having the ability to significantly reduce T_{max} (maximum temperature rise of the battery module) with minimal compromise.

Despite the significance of this particular field of research, it has remained underdeveloped yet. This paper presents a quantitative evaluation of the existing works on parametric analyses of BTMS, focusing on the effects of various input parameters on maximum temperature rise of the battery module. Furthermore, it provides a thorough overview of the current state of research and identifies the key research gaps.

2. Bibliometric Analysis of Parametric Analyses on Battery Thermal Management Systems

A database search employing the query string 'Battery Thermal Management Systems' within the search index 'Title and abstract' yielded 5832 research documents in the 'Dimensions' database. Extending the query string to 'Parametric Analysis in Battery Thermal Management Systems' cuts down the number of scholarly articles to only 45, a minimal fraction of the publications on 'Battery Thermal Management Systems'. The following sections assess the scholarly works yielded based on the latest query. In order to generate graphical representation of the data obtained for analysis, OriginPro (version 2018, OriginLab Corporation) was employed. VOSviewer, a bibliometric network analysis program, was utilized to examine the collaborative relationships between countries. Within the search filter 'Publication Year', the 45 research articles extracted have been classified as per the year of publication to establish a numerical pattern of the research trajectory, which is demonstrated in **Figure 1.**

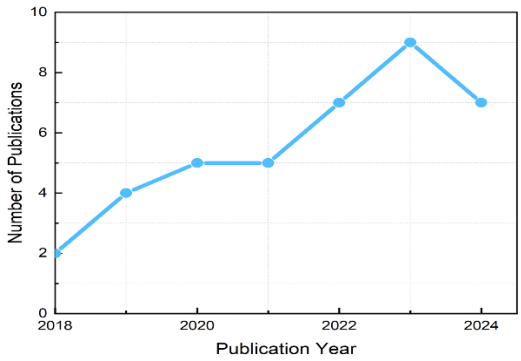


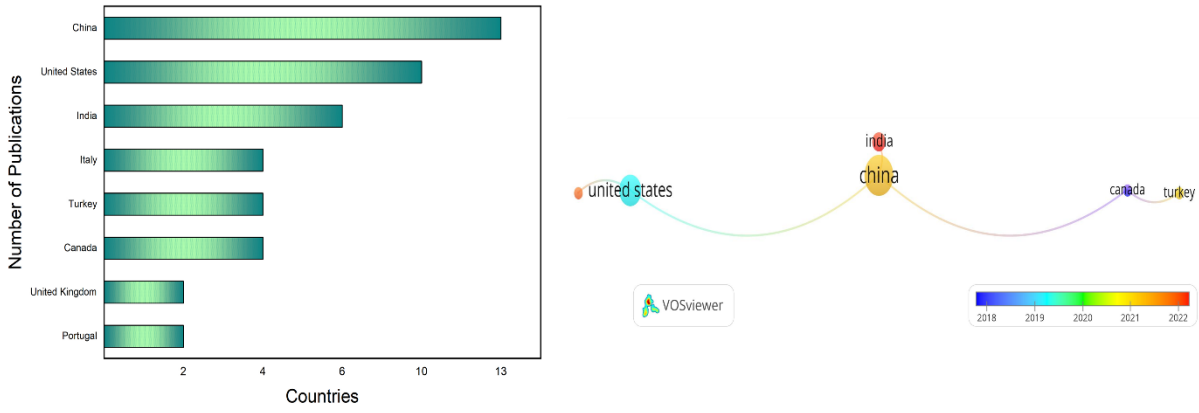
Fig. 1. Trend in number of research articles published annually.

Figure 2(a) represents the top 10 nations with the highest number of published research articles, while **Figure 2(b)** demonstrates the collaborative relationship between countries working in the previously stated research topic, through an overlay visualization map representing the distribution of publications based on the type of analysis 'citation' and chosen unit of analysis 'countries', for the countries having at least 4 documents and publications having a minimum of 2 citation. The network map highlights research output by a nation, utilizing the diameter of the nodes to reflect the publication volume of that region, and the color of the nodes to reveal average year of publication. The thickness of the line between the nodes represents collaboration strength between nations.

3. Comprehensive Evaluation of Existing Parametric Analyses of BTMS

A critical analysis of the previously conducted parametric analyses of available thermal management approaches for Li-ion battery systems is imperative to have a comprehensive understanding of the contemporary research landscape and to identify further research areas. Despite the increasing demand to comprehend this specific area for improved performance, limited research has been conducted in recent years. L. Fan et al. (2013) [6] investigated an air-cooled unit, housing prismatic Li-ion cells, employing equidistant air-flow channels positioned bilaterally on each cell. The parameters taken into consideration were space between channels, air flow rate, uniformity of gap spacing and the directionality of the channel placement. It was observed that lower gap spacing and higher flow rate of air decreased the peak temperature increase of the module. Further investigations after optimizing the module with a moderate spacing between channels and an air flow rate for maximizing the performance demonstrated the lower effectiveness of the unilateral placement of the channels in comparison with

their bilateral placement, and the negligible impact of the uniformity of the gap spacing on the overall performance of the air-cooled TMS [6]. Abhishek Sarkar et.al. (2018) [7], characterized 6 different materials for electrodes based on five performance indicators, computing the heat gain from four plausible mechanisms. Depending on the results obtained, lithium ferrous phosphate and silicon were selected as the best suited cathode and anode materials respectively, for improved thermal stability and extended lifespan[7]. Table 1 represents a concise overview of a selection of research works on parametric investigations of available BTM strategies, published over the last 4 years (2021-2024), which provides a brief insight into their respective contents.



(a) (b)

Fig. 2. (a) Top 8 countries with the highest number of research articles and (b) Collaborative relationships between countries.

Table 1. Summary of parametric investigations carried out on battery thermal management systems (Here, Increased = I, Decreased = D, Flow velocity = v, Melting point = m.p., Diameter = Dia., Temperature =T, Number = No., Discharge rate = q, Ethylene Glycol = EG, Cell Spacing = $\overline{w_f}$, Volumetric heat generation = $\bar{S}_q$, Conduction-convection parameter = ζ_{cc}, Thermal conductivity = k, Latent heat of evaporation = L_v, Mass flow rate = $\dot{m}$, Specific heat capacity = c)

SN	Year	Battery Variant	Cooling System	Variable parameters	Observations	Ref.
1.	2021	Prismatic Li-ion battery	Helical liquid channel-cooled PCM/copper foam composite BTMS	Channel shape (Straight and Helical); Helical pitch; Helical dia.; Tube No.; v; Pore density and porosity; PCM m.p.	Factors improving cooling performance: Using helical channel; Helical Pitch (D); Helical dia. (I); Tube No. (I); v (I) up to 0.05 m/s; Pore density (I); Porosity – 0.92; PCM m.p. (D)	[8]
2.	2021	20 Ah, 3.3 V pouch-type $LiFePO_4$ battery	Cold plate with straight mini-channels	Coolant type; No. of Channels; Channel Width; $\dot{m}$; Coolant T at inlet; Ambient T; q	Optimum conditions for improved cooling performance: Coolant – Tropical region (Water), Colder region (Mixture of water and EG); No. of channels – 5; Channel width = 6 mm; $\dot{m}$ = 3×10-³ kg/s; Coolant T at inlet = Between 20 °C and 30 °C; Ambient T = Around 25 °C; q (D)	[9]
3.	2021	Prismatic Li-ion battery	Air-cooled BTMS	$\overline{w_f}$; $\bar{S}_q$; ζ_{cc}	Factors improving cooling performance: Concurrent increase of ζ_{cc} and $\overline{w_f}$	[10]

SN	Year	Battery Variant	Cooling System	Variable parameters	Observations	Ref.
4.	2021	24-cell battery pack utilizing cylindrical 18650 Li-ion cells	Air-cooled BTMS	Channel spacing in X- and Y-directions, Air inlet velocity	Factors improving cooling performance: Channel spacing: X-direction (D), Y-direction (D), Air inlet velocity (I)	[11]
5.	2022	25 Ah, pouch-type Li-ion cell	BTMS based on direct evaporative cooling	Initial T; Inlet v; Saturation T; k, L_v of Coolant	Factors improving cooling performance: Initial T (D); Inlet v (I); Saturation T (D); k (I), L_v (I)	[12]
6.	2022	24 Ah, pouch-type Li-ion cell	Immersion cooling	$\dot{m}$; viscosity; c; k	Factors improving cooling performance: $\dot{m}$ (I); viscosity (no effect); c (I); k (I)	[13]
7.	2022	50 Ah, prismatic Li-ion cell	Two-phase pumped cooling BTMS	Saturation T; Mass flux; Subcooling degree	Factors improving cooling performance: Saturation T (D); Mass flux (I); Subcooling degree (I)	[14]
8.	2023	33-cell battery pack utilizing cylindrical 18650 Li-ion cells	Cold plate with wavy microchannel (MC) coupled with PCM	PCM thickness; No. of MC; Flow direction; $\dot{m}$; phase transition T	Factors improving cooling performance: PCM thickness (I); No. of MC (I); Flow direction (Cross flow); $\dot{m}$ (I); phase transition T (D)	[15]
9.	2024	2.4 Ah, cylindrical 18650 Li-ion battery	BTMS employing fins, PCM and metal foams	Materials for fins and metal foams; Fin length; No. of fins	Factors improving cooling performance: Materials for fins and metal foams (Copper); Fin length (I); No. of fins (I)	[16]
10.	2024	Battery pack utilizing cylindrical 18650 Li-ion cells	Air-cooled BTMS	Air inlet velocity; q; Air inlet T	Factors improving cooling performance: Air inlet velocity (I); q (D); Air inlet T (D)	[17]

4. Discussion

Section 2 statistically evaluates the current scenario of existing research works on parametric studies of battery thermal management techniques. A notable lack of research is clearly evident while bibliometrically analyzing this topic, from

- the substantial difference in search results, representing ‘parametric analysis’ as a nearly unexplored field in the huge research area of battery thermal management systems
- the inadequate collaborative research relationship between countries, as demonstrated by the network map plotted

Section 3 summarizes the key findings from available publications:

- In comparison to other cooling strategies, air-cooled BTMS are found to be the subject of a greater number of parametric studies suggesting a deeper comprehension of their design specifications and optimization potential. During these analyses, inlet velocity of air passing through the thermal management module is one independent variable considered frequently to observe its impact on cooling performance of the module, increasing which significantly improves the cooling efficiency.
- Cooling systems employing cold plates, channels and liquid as a coolant have also gained some attention in this area of study. For cooling systems utilizing channels, important parameters taken into consideration are number of coolant channels and channel spacing. From the studies above, lowering gap spacing with increased number of channels typically have a positive effect on the overall cooling performance.
- For both air-cooled and liquid-cooled BTMS, lower inlet temperature of the cooling fluid, along with a lower saturation temperature for liquid coolants, enhance the effectiveness of the coolant.
- PCM and metal foam are also employed as heat transfer agent for parametric studies of BTMS, where different variables parameters are taken into consideration. However, insufficient number of studies done leads to a failure to draw any valid conclusion about their impact on cooling performance of these agents.
- Noteworthy focus has been drawn on hybrid cooling technologies, comparing their efficiencies with that of conventional cooling techniques. The hybrid technologies show an enhancement in their performance in comparison with the latter.

5. Conclusions

The study highlighted the importance of an efficient battery thermal management system in electric vehicles and the significance of parametric analysis in thermal management technologies. Bibliometric analysis and critical evaluation of the available research articles have been conducted. Based on the literature review, below presented are few conclusive remarks:

- Air-cooled and hybrid battery thermal management systems have been a focus to greater number of parametric studies.
- For air-cooled BTMS, high inlet velocity and lower inlet temperature of air reduces T_{max}.
- For channel-based cooling systems, lower gap spacing reduces $T_{max.}$
- For liquid-cooled BTMS, lower inlet and saturation temperature of coolant enhances coolant effectiveness.
- Hybrid BTMS offer better performance than conventional ones.

This study provides a scenario for the research gap on parametric analysis of battery thermal management systems. Future research will focus on parameter-based study on more BTM technologies and specific properties of each strategy for optimization of battery thermal management systems with enhanced performance.

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