



Journal Homepage: [-www.journalijar.com](http://www.journalijar.com)

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/24382
DOI URL: <http://dx.doi.org/10.21474/IJAR01/24382>



RESEARCH ARTICLE

IMPROVING THERMAL COOLING SYSTEMS FOR ELECTRIC VEHICLE BATTERIES: A COMPARATIVE NUMERICAL STUDY AND META-ANALYSIS

Idrees M. A. Alkandari

1. Sabah Alsalem Industrial Institute, PAAET, Kuwait.

Manuscript Info

Manuscript History

Received: 12 August 2026

Final Accepted: 14 September 2026

Published: October 2026

Key words:-

Battery thermal management, electric vehicles, hybrid cooling, immersion cooling, lithium-ion battery, meta-analysis, phase change material.

Abstract

The thermal management of the lithium-ion battery is one of the main factors which determine the safety, the fast-charging capability and the service life of the electric vehicles, and this is applied especially on the hot climates such as the Gulf region. In this paper, a reduced-order thermal network of a ten-cell 21700 module was developed, and it was used to compare six cooling strategies, namely the natural air, the forced air, the indirect liquid cold plate, the phase change material (PCM), the hybrid PCM-liquid and the single-phase immersion cooling, at the discharge rates of 1C, 2C and 3C and at the ambient temperatures of 25 °C and 40 °C. In addition, a random-effects meta-analysis of eight published comparisons was conducted. The results showed that, at 3C and 25 °C, the peak core temperature was reduced from 58.27 °C under the natural air to 34.02 °C under the immersion cooling and to 34.45 °C under the hybrid PCM-liquid system. Moreover, when a coolant pump failure was simulated at 40 °C, the hybrid system limited the peak temperature to 44.79 °C, while the cold plate reached 59.42 °C. The meta-analysis gave a pooled reduction of the maximum temperature of 9.51 °C (95% CI 7.48 to 11.55 °C) with a high heterogeneity ($I^2 = 92.7\%$). These results suggest that the hybrid PCM-liquid architecture gives a good balance between the cooling performance and the fault tolerance, and this makes it a suitable candidate for the electric vehicles which operate in hot climates.

"© 2026 by the Author(s). Published by IJAR under CC BY 4.0. Unrestricted use allowed with credit to the author."

Introduction:-

The electric vehicles are considered now as the main option for reducing the emissions of the road transport, and the lithium-ion battery is the most expensive and the most sensitive component in these vehicles. The performance of the lithium-ion cell depends strongly on the temperature, where the recommended operating window is usually between 15 °C and 40 °C, and the cell-to-cell temperature difference should be kept below about 5 °C. When the temperature exceeds this window, the aging of the cell is accelerated, and in the extreme cases the thermal runaway can be triggered [1]. Accordingly, the battery thermal management system (BTMS) is a necessary part in every electric vehicle, and the design of the BTMS became more difficult with the increase of the fast-charging rates. Several cooling technologies were proposed in the previous studies. The air cooling is simple and cheap, but the low heat capacity of the air limits its ability at the high C-rates. The indirect liquid cooling with the cold plates is

Corresponding Author:- Idrees M. A. Alkandari

Address:- Sabah Alsalem Industrial Institute, PAAET, Kuwait.

the dominant solution in the commercial vehicles, and the previous studies showed that the position of the coolant channel affects the performance strongly, for example the inter-cell channel gave a peak temperature rise of 4.1 °C compared with 14.2 °C for the edge cooling under 5C charging [2], [3]. On the other hand, the passive PCM absorbs the heat as a latent heat, and the hybrid PCM-liquid systems combine the both mechanisms [4], [5]. Moreover, the single-phase and the two-phase immersion cooling in a dielectric fluid received a big attention recently because the fluid contacts the whole surface of the cell [6], [7], [8], [9], [10].

However, it should be noted that most of the previous researches studied one cooling technology under one ambient temperature, and the comparison between the technologies was made usually against a different baseline in each study. Furthermore, the behavior of the BTMS under a failure of the active component, such as the pump, was rarely reported, although this scenario is important for the safety. With regard to the hot climates, where the ambient temperature in summer exceeds 45 °C, the control of the battery temperature is more difficult, and the optimal control strategies were proposed for the extreme ambient conditions [11]. For this reason, the current study compares six cooling strategies under the same conditions by using a reduced-order thermal model of a 21700 module. The performance is evaluated at 25 °C and at 40 °C, and also under a pump failure scenario, which received little attention in the previous studies. In addition, the published results are synthesized through a quantitative meta-analysis, so that the ranking obtained from the simulation can be checked against the experimental and the numerical evidence of other research groups, and a practical design guidance can be given for the electric vehicles in the hot climates.

Methodology:-

Reduced-Order Thermal Model:-

A module of ten 21700 cells (5 Ah) connected in series along the coolant flow path was considered. Each cell was represented by a two-node model, which consists from a core node and a surface node, and the heat generation was calculated from the irreversible Joule term of the energy balance of Bernardi et al. [12], where the reversible entropic term was neglected:

$$C_c \, dT_c/dt = I^2 R(T_c) - (T_c - T_s)/R_{cs} \quad (1)$$

$$C_s \, dT_s/dt = (T_c - T_s)/R_{cs} - hA_c(T_s - T_f) \quad (2)$$

where C_c and C_s are the heat capacities of the core and the surface, R_{cs} is the core-to-surface thermal resistance, h is the heat transfer coefficient, A_c is the cooled area and T_f is the local coolant temperature. The internal resistance was taken as 20 mΩ at 25 °C with an Arrhenius temperature dependence, and a random spread of ±5% was added to the resistance of the cells in order to represent the manufacturing variation. The coolant temperature was increased from cell to cell according to the energy balance of the fluid, and this gives the cell-to-cell temperature difference ΔT . For the PCM cases, a third node was added for a paraffin and expanded graphite composite with a melting range of 36 to 40 °C and a latent heat of 180 kJ/kg, and the enthalpy method was used. The equations were integrated with an explicit scheme and a time step of 1 s. The main parameters are given in Table I.

Table I Main Parameters Of The Cooling Configurations

Configuration	h (W/m ² K)	Area	Coolant / inlet
Natural air	7	100%	none / ambient
Forced air	45	100%	air, 4 g/s / ambient
Cold plate	900	20%	glycol, 10 g/s / 25 °C
PCM	7 (outer)	100%	30 g PCM per cell
Hybrid PCM-liquid	900	20%	glycol + PCM / 25 °C
Immersion	320	100%	dielectric oil, 30 g/s / 25 °C

Cell: 21700, 5 Ah, 68 g, $c_p = 1100 \text{ J/kgK}$, $R_{cs} = 1.8 \text{ K/W}$, $R_0 = 20 \text{ m}\Omega$ at 25 °C.

Test Scenarios and Indicators:-

Three scenarios were simulated. In the first scenario, a constant-current discharge at 1C, 2C and 3C was applied at the ambient temperatures of 25 °C and 40 °C, where the cells start at the ambient temperature. In the second scenario, an aggressive duty cycle was applied at 40 °C, which consists of two repetitions of a 3C discharge, a 10 min rest, a 2C charge and another rest. In the third scenario, the coolant pump was stopped after 5 min of a 3C discharge at 40 °C, and only the natural convection remains. The indicators were the peak core temperature T_{max} , the maximum cell-to-cell difference ΔT , and a relative aging factor which is the time-average of $\exp[(E_a/R)(1/298.15 - 1/T_c)]$ with $E_a = 31.5$ kJ/mol [1]. The parasitic power of the fan or the pump was estimated from the pressure drop and the flow rate with an efficiency of 0.5.

Meta-Analysis Procedure:-

The published studies which report the maximum temperature of a cooling technology and of a baseline under the same conditions were collected, and the effect size was defined as the reduction of T_{max} relative to the baseline of each study. Eight comparisons from six studies were included [2], [4], [5], [6], [13], [14], as it is shown in Table III. As for the within-study variance, the studies did not report it, therefore the standard error was assumed as 0.71 °C for the experimental studies (± 0.5 °C thermocouple accuracy on two readings) and 1.0 °C for the numerical studies. The pooled effect was estimated by the DerSimonian-Laird random-effects model [15], and the heterogeneity was measured by the Q statistic and the I^2 index [16]. Two sensitivity analyses were performed, the first one by doubling all the variances and the second one by keeping only the experimental studies.

Results:-

Comparison of the Cooling Strategies:-

Fig. 1 presents the peak core temperature for all the configurations. At 25 °C and 1C, all the strategies kept the cells below 36 °C, and the difference between them was small. However, the difference became large with the increase of the C-rate. At 3C, the natural air reached 58.27 °C and the forced air reached 45.35 °C, which is on the limit of the safe window, while the cold plate, the hybrid system and the immersion cooling kept the peak temperature at 35.34 °C, 34.45 °C and 34.02 °C, respectively. The PCM alone gave 43.02 °C, and it was better than the forced air, but the PCM was fully melted near the end of the discharge.

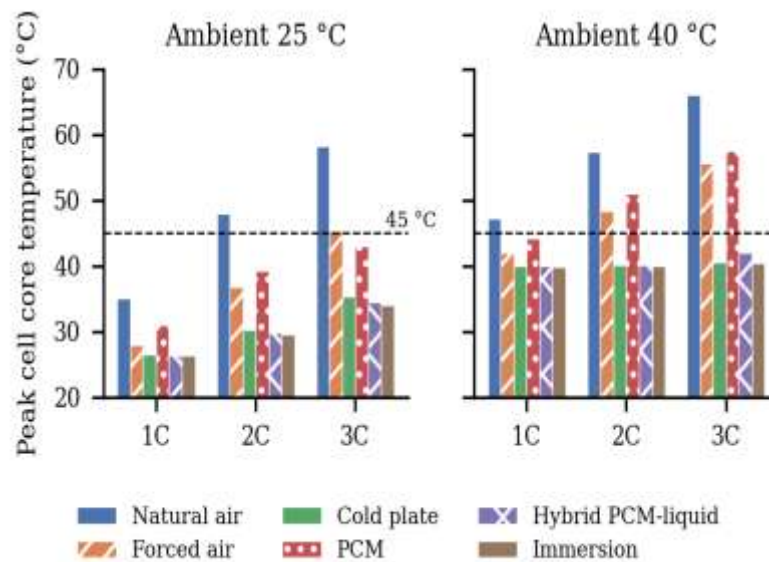


Fig. 1. Peak cell core temperature at the end of a constant-current discharge for the six cooling strategies at 25 °C and 40 °C ambient. The dashed line shows the 45 °C limit.

At the ambient temperature of 40 °C, the situation is different. The strategies which depend on the ambient air, namely the natural air, the forced air and the PCM, exceeded 55 °C at 3C, and this is because the driving temperature difference between the cell and the air was reduced. In addition, it should be noted that the PCM lost most of its benefit at 40 °C, since the material was already at its melting range before the discharge started, and therefore the latent heat was not available. As for the liquid-based systems with a chilled coolant at 25 °C, the cells

were cooled down from the initial 40 °C during the discharge, and the peak temperature remained close to the initial value. The detailed values at 3C are given in Table II.

Table II Simulated Performance At 3c Discharge

Strategy	T _{max} 25	ΔT 25	T _{max} 40	ΔT 40	Aging 40	P (W)
Natural air	58.27	3.50	66.05	3.04	3.30	0
Forced air	45.35	3.92	55.56	3.20	2.74	1.30
Cold plate	35.34	1.32	40.55	1.32	1.55	0.09
PCM	43.02	2.02	57.48	2.19	2.76	0
Hybrid PCM- liq.	34.45	1.23	41.96	3.08	1.69	0.09
Immersion	34.02	1.18	40.33	1.18	1.46	0.70

Temperatures in °C at 25 and 40 °C ambient. Aging: relative Arrhenius rate (1.0 = 25 °C). P: fan or pump power per 10-cell row, chiller power not included. Regarding the temperature uniformity, the immersion and the hybrid systems gave the lowest ΔT at 25 °C (1.18 °C and 1.23 °C), while the forced air gave the highest value (3.92 °C) because the air was heated along the row of the cells. In addition, the relative aging factor at 40 °C was 3.30 for the natural air and only 1.46 for the immersion cooling, which means that the cells under the natural air age about 2.3 times faster than the cells under the immersion cooling.

Duty Cycle and Pump Failure:-

Under the aggressive duty cycle at 40 °C, the natural air reached 70.12 °C and the PCM reached 59.86 °C, while the cold plate, the hybrid and the immersion systems stayed at 40.55 °C, 41.96 °C and 40.33 °C, respectively. Fig. 2 shows the transient response at 3C and 40 °C including the pump failure. When the pump was stopped at 5 min, the cold plate temperature increased fast and reached 59.42 °C, and the immersion cooling reached 59.40 °C. In contrast, the hybrid PCM-liquid system was limited to 44.79 °C, which is 14.63 °C lower than the cold plate, because the PCM which was kept solid by the liquid before the failure absorbed the heat during the rest of the discharge.

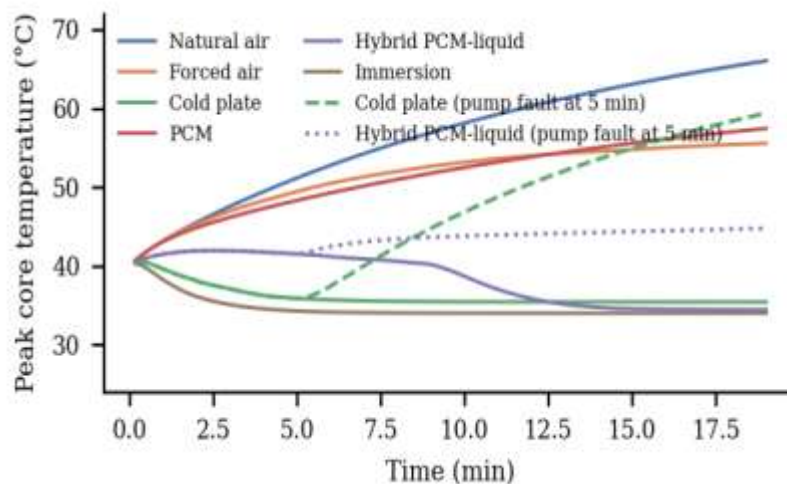


Fig. 2. Transient peak core temperature at 3C and 40 °C ambient. The dashed and dotted lines show the cold plate and the hybrid system when the coolant pump fails after 5 min.

Meta-Analysis of the Published Studies:-

The included comparisons are summarized in Table III and the forest plot is given in Fig. 3. All the eight comparisons showed a reduction of the maximum temperature, and the effects ranged from 3.44 °C to 14.0 °C. The random-effects pooled reduction was 9.51 °C (95% CI 7.48 to 11.55 °C), with $Q = 96.11$, $\tau^2 = 7.93$ and $I^2 = 92.7\%$,

which indicates a high heterogeneity between the studies. With regard to the subgroups, the liquid cooling gave 10.79 °C (7.93 to 13.64, $k = 3$), the PCM gave 9.65 °C (5.14 to 14.15, $k = 2$), the hybrid systems gave 5.87 °C (1.21 to 10.54, $k = 2$), and the single immersion study gave 12.5 °C.

Table Iii Comparisons Included In The Meta-Analysis

Study	Type	Comparison	Effect (°C)
Sundin [6]	Exp	Immersion vs forced air, 1C	12.5
Chen [4]	Exp	PCM vs no cooling, 3C charge	7.4
Chen [4]	Exp	Liquid vs no cooling, 3C charge	8.5
Chen [4]	Exp	Hybrid vs no cooling, 3C charge	8.2
Karimi Kisomi [14]	Num	PCM vs air, finless cell	12.0
Zhao [2], [3]	Exp	Inter-cell vs edge liquid, 5C	10.1
Rabiei [13]	Num	Metal-foam vs straight channel	14.0
Lyu [5]	Num	Hybrid vs conventional liquid, 1C	3.44

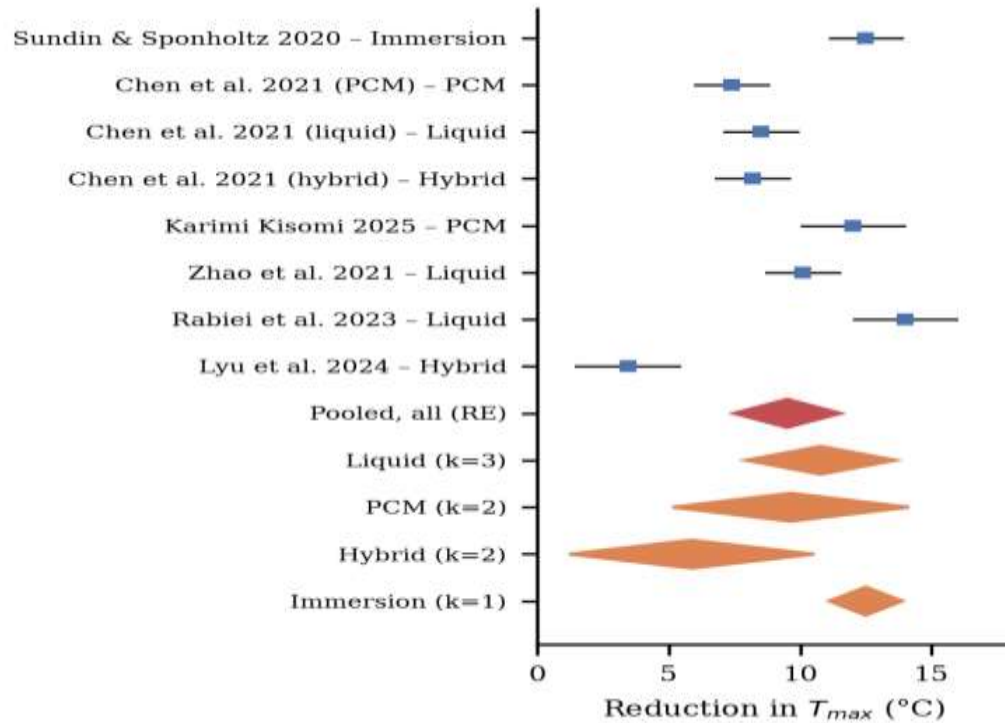


Fig. 3. Forest plot of the reduction in the maximum temperature relative to the baseline of each study (95% CI), with the random-effects pooled estimate and the subgroup estimates.

The sensitivity analyses confirmed the stability of the pooled estimate. When the variances were doubled, the pooled reduction was 9.51 °C (7.47 to 11.54 °C), and when only the five experimental comparisons were kept, the pooled reduction was 9.34 °C (7.57 to 11.11 °C).

Discussion:-

The results of the simulation and the results of the meta-analysis are consistent in the ranking of the technologies. Both of them place the liquid-based systems and the immersion cooling at the top, and the PCM in a moderate position, although the confidence intervals of the subgroups in the meta-analysis overlap and the ranking from the meta-analysis alone is not conclusive. The smaller pooled effect of the hybrid subgroup should not be interpreted as a weak performance of the hybrid systems, because the study of Lyu et al. [5] compared the hybrid system against a conventional liquid system, which is already a strong baseline, while the other studies compared against the air or the no-cooling case. Therefore, the high heterogeneity is explained mainly by the difference of the baselines and of the C-rates, and this is a known problem in the BTMS literature, where a common benchmark condition is missing. Furthermore, the cold plate design itself causes a large variation, and Sevilgen et al. [17] reported a reduction of the maximum temperature up to 45% only by changing the cold plate geometry.

As for the hot climates, the current study shows two important points. The first point is that any strategy which rejects the heat directly to the ambient air is not sufficient at 40 °C and 3C, and a chilled liquid loop is required. The second point is that the melting point of the PCM must be selected above the hot-soak temperature of the parked vehicle, otherwise the PCM is melted before the driving and it gives no protection. This choice depends on the local climate, and for the Gulf region a melting point near 45 °C may be more suitable. With regard to the safety, the pump failure scenario showed that the active systems lose their advantage completely when the coolant stops, and the temperature returns to the level of the natural convection. The hybrid system keeps a passive thermal buffer, and accordingly it gives a time margin for the battery management system to reduce the current or to warn the driver. On the other side, the immersion cooling gave the best uniformity and the lowest aging factor, but it requires a dielectric fluid and a higher pump power (0.70 W per row compared with 0.09 W for the cold plate), and the long-term compatibility of the fluid with the cell materials is still under investigation [9], [10]. The limitations of this study should be mentioned. The thermal model is a reduced-order model and it was not validated against a specific experiment, the entropic heat was neglected, and the heat transfer coefficients were taken from the typical ranges and not from a CFD analysis. In addition, the meta-analysis included a small number of comparisons and the within-study variances were assumed, therefore the confidence intervals should be considered as approximate.

Conclusion and Future Directions:-

In this paper, six cooling strategies for the electric vehicle battery were compared by a reduced-order thermal model at 25 °C and 40 °C, and the published results were synthesized by a random-effects meta-analysis. The main conclusions are as follows. At 3C, the immersion and the hybrid PCM-liquid systems reduced the peak temperature from 58.27 °C to about 34 °C. At 40 °C, only the chilled liquid systems kept the cells near the safe limit. Under a pump failure, the hybrid system limited the temperature to 44.79 °C, while the cold plate reached 59.42 °C. The pooled published reduction of the maximum temperature was 9.51 °C with a high heterogeneity. Several directions remain open for the future work. The most important next step is an experimental validation of the hybrid system under the summer conditions of the Gulf region, because the present model was not validated against a specific test. In addition, the field needs a common benchmark protocol which fixes the cell format, the C-rate, the ambient temperature and the baseline, since the high heterogeneity found in this study comes mainly from the different baselines. The PCM with a higher melting point and the nano-enhanced composites also deserve more attention for the high ambient temperatures. Lastly, the integration of the predictive control and the machine learning with the BTMS, as in the optimal control of [11], may reduce the energy consumption of the chiller during the fast charging.

References:-

- [1] J. Wang et al., "Cycle-life model for graphite-LiFePO₄ cells," J. Power Sources, vol. 196, no. 8, pp. 3942–3948, 2011.
- [2] Z. Zhao, P. J. Kollmeyer, J. M. Lempert, and A. Emadi, "Experimental comparison of two liquid cooling methods for ultrafast charging lithium-ion battery modules," in Proc. IEEE Transp. Electrification Conf. Expo (ITEC), 2021, pp. 46–51.
- [3] Z. Zhao, "Testing and thermal management system design of an ultra-fast charging battery module for electric vehicles," M.A.Sc. thesis, McMaster Univ., Hamilton, ON, Canada, 2021.
- [4] S. Chen et al., "An experimental investigation for a hybrid phase change material-liquid cooling strategy to achieve high-temperature uniformity of Li-ion battery module under fast charging," Int. J. Energy Res., vol. 45, no. 4, pp. 6198–6212, 2021.
- [5] Z. Lyu et al., "A compact hybrid battery thermal management system for enhanced cooling," arXiv:2412.00999, 2024.

- [6] D. W. Sundin and S. Sponholtz, "Thermal management of Li-ion batteries with single-phase liquid immersion cooling," *IEEE Open J. Veh. Technol.*, vol. 1, pp. 82–92, 2020.
- [7] N. P. Williams, D. Trimble, and S. M. O'Shaughnessy, "Liquid immersion thermal management of lithium-ion batteries for electric vehicles: An experimental study," *J. Energy Storage*, vol. 72, Art. no. 108636, 2023.
- [8] N. P. Williams, D. Trimble, and S. M. O'Shaughnessy, "An experimental investigation of liquid immersion cooling of a four cell lithium-ion battery module," *J. Energy Storage*, vol. 86, 2024.
- [9] P. M. Tripathi and A. M. Marconnet, "Multi-physics numerical analysis of single-phase immersion cooling for thermal management of Li-ion batteries," *J. Power Sources*, vol. 632, Art. no. 236285, 2025.
- [10] C. Suresh, A. Awasthi, B. Kumar, S.-K. Im, and Y. Jeon, "Advances in battery thermal management for electric vehicles: A comprehensive review of hybrid PCM-metal foam and immersion cooling technologies," *Renew. Sustain. Energy Rev.*, vol. 208, 2025.
- [11] Z. Lu, H. Tu, H. Fang, Y. Wang, and S. Mou, "Integrated optimal control for fast charging and active thermal management of lithium-ion batteries in extreme ambient temperatures," *IEEE Trans. Control Syst. Technol.*, 2024.
- [12] D. Bernardi, E. Pawlikowski, and J. Newman, "A general energy balance for battery systems," *J. Electrochem. Soc.*, vol. 132, no. 1, pp. 5–12, 1985.
- [13] M. Rabiei, A. Gharehghani, and A. M. Andwari, "Enhancement of battery thermal management system using a novel structure of hybrid liquid cold plate," *Appl. Therm. Eng.*, vol. 232, Art. no. 121051, 2023.
- [14] M. Karimi Kisomi, "Thermal management of lithium-ion batteries: A comparative study of phase change materials and air-cooling systems equipped with fins," *arXiv:2503.10244*, 2025.
- [15] R. DerSimonian and N. Laird, "Meta-analysis in clinical trials," *Control. Clin. Trials*, vol. 7, no. 3, pp. 177–188, 1986.
- [16] J. P. T. Higgins and S. G. Thompson, "Quantifying heterogeneity in a meta-analysis," *Stat. Med.*, vol. 21, no. 11, pp. 1539–1558, 2002.
- [17] G. Sevilgen, H. Dursun, and M. Kılıç, "Experimental and numerical investigations on the thermal performance of three different cold plates designed for the electrical vehicle battery module," *Sustainability*, vol. 15, no. 19, Art. no. 14162, 2023.