IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Advanced Thermal Management Systems for Lithium-Ion Battery Packs Utilizing Nano-material Enhanced Hybrid Control Techniques: A Comprehensive Review

[1]Mr. Mohd Aadil Shaikh Ab. Rahim, [2]Mr. Prof.Kishor M. Mahajan, [3]Mr. Dr Tushar A. Koli, [4]Mr. Prof. Mayur P. Thakur

[1]PG Student, [2]Asst. Professor, [3]Associate. Professor ,[4]Asst. Professor

Department of Thermal Engineering,

GF's Godavari College of Engineering, Jalgaon,425001

Maharashtra, India

Abstract – *The rapid proliferation of high-energy-density Lithium-ion Batteries (LIBs) in electric vehicles and grid-scale storage has shifted the critical bottleneck from energy capacity to thermal stability. Conventional air and liquid cooling methods increasingly struggle to manage the localized heat flux generated during Extreme Fast Charging (XFC) and high-discharge cycles, often leading to capacity fade or catastrophic thermal runaway. This review evaluates the transition from macro-scale cooling to nanomaterial-based thermal control, focusing on the integration of nanotechnology within passive and active cooling architectures. The analysis first explores Nano-enhanced Phase Change Materials (NePCMs), where the incorporation of high-conductivity fillers—such as Graphene, Carbon Nanotubes (CNTs), and metallic nanoparticles (Al2O3, CuO) addresses the inherent low thermal conductivity of organic waxes. Evidence suggests that a 1\% to 5\% weight fraction of carbon-based nano materials can improve thermal response times by up to 160%, effectively smoothing peak temperature spikes.*

Keywords*- Lithium-ion Battery (LIB), Thermal Management System (BTMS), Nanofluids, Phase Change Materials (PCM), Graphene, Thermal Runaway, Heat Transfer Enhancement.*

INTRODUCTION

Lithium-ion (Li-ion) batteries have become a key technology in electric vehicles (EVs) and renewable energy storage systems due to their high energy density, long cycle life, and reliable performance [1]. Their increasing adoption supports the transition toward sustainable energy and low-emission transportation systems. During operation, Li-ion batteries generate heat due to internal resistance, electrochemical reactions, and polarization effects, particularly under high charge–discharge rates [2]. This heat accumulation can lead to elevated temperatures and non-uniform thermal distribution within battery cells and modules. Excessive temperature rise results in several adverse effects, including accelerated degradation, reduced efficiency, capacity fading, and shortened battery lifespan. More critically, overheating can trigger thermal runaway, leading to hazardous conditions such as fire or explosion [3]. Therefore, maintaining an optimal temperature range is essential for ensuring safe and efficient battery operation. To mitigate these issues, Battery Thermal Management Systems (BTMS) are employed to control and regulate battery temperature [4]. Conventional BTMS techniques, such as air cooling, liquid cooling, and phase change materials (PCMs), are widely used; however, they often suffer from limitations in heat transfer efficiency and increased system complexity. Recently, nanostructured materials have emerged as promising candidates for enhancing thermal management performance. Materials such as nanofluids, graphene, and carbon nanotubes (CNTs) exhibit high thermal conductivity, large surface area, and improved thermo physical properties, enabling more efficient heat dissipation [5].Despite extensive research, existing studies are often limited in scope and lack a comprehensive evaluation of nanomaterial-based thermal control techniques in Li-ion battery systems.

The objective of this paper is to analyze various nanomaterial-based techniques, evaluate their heat transfer mechanisms, and assess their effectiveness in improving the performance, safety, and reliability of lithium-ion battery systems.

2. LITERATURE REVIEW

2.1 Experimental Studies on Nano-Enhanced Thermal Management: Recent experimental efforts have heavily focused on addressing the low thermal conductivity of traditional cooling mediums by introducing carbon-based or metallic nanoparticles. Base materials, such as Phase Change Materials (PCMs) or dielectric liquid coolants, often suffer from heat saturation during rapid charging and discharging cycles. Researchers have experimentally demonstrated that doping these mediums with nano materials like Graphene, Multi-Walled Carbon Nanotubes (MWCNTs), and metallic oxides (e.g., Al_2O_3, CuO) drastically improves heat dissipation. Experimental setups typically involve testing cylindrical or prismatic lithium-ion battery packs under varying discharge rates (e.g., 1C to 5C). Empirical data consistently shows that Nano-Enhanced PCMs (NEPCMs) can effectively maintain the maximum surface temperature of batteries below the critical 50°C threshold, significantly reducing the temperature differential between individual cells compared to baseline thermal management systems.

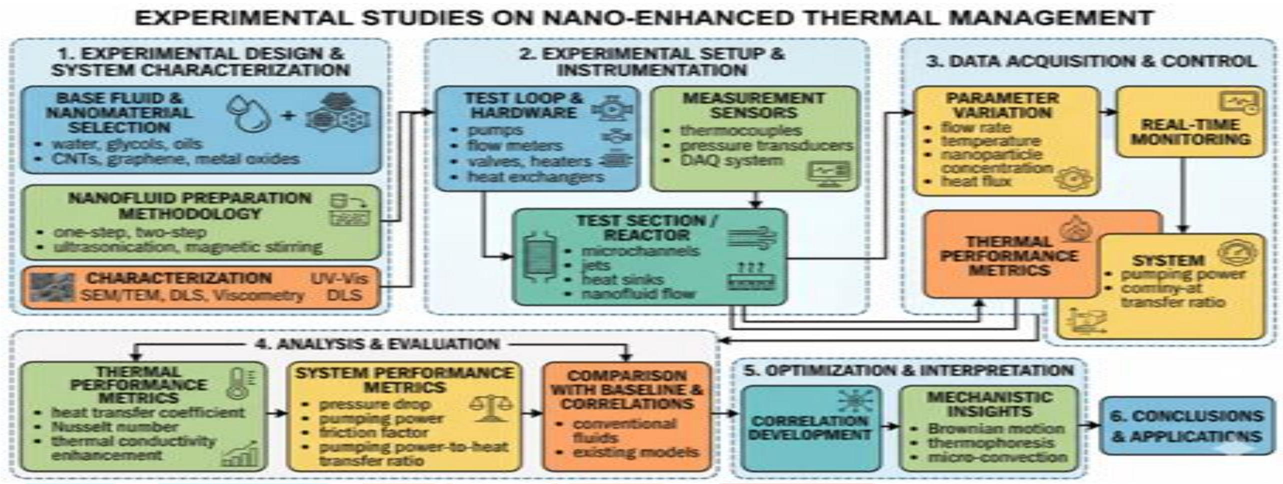

Fig.1- fig shows the Experimental Studies on Nano-Enhanced Thermal Management

2.2 Numerical and Simulation Studies**:** While experimental studies provide tangible validations, numerical and simulation studies—primarily utilizing Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) software like ANSYS Fluent or COMSOL—allow for rapid, cost-effective parametric optimization. Numerical research has been instrumental in predicting the complex thermo-physical behaviors of nanofluids and the melting/solidification kinetics of NEPCMs. Recent simulations have explored the effects of varying nanoparticle volume fractions, coolant flow rates, and micro channel geometries. For example, CFD models have proven that modifying the layout of liquid cooling pipes (such as utilizing serpentine or U-shaped micro channels in conjunction with Al_2O_3-water nanofluids can yield up to a 40% improvement in heat transfer rates. These models are crucial for mapping localized hotspots and validating the structural integrity of the battery module without the need for exhaustive physical prototyping.

2.3 Hybrid Thermal Management Using Nanomaterials: A single cooling approach is rarely sufficient for modern, high-energy-density electric vehicle (EV) batteries. Consequently, the literature shows a distinct shift toward hybrid Battery Thermal Management Systems (BTMS) that combine both active and passive cooling techniques. A prevalent hybrid configuration involves embedding battery cells in a passive NEPCM matrix to absorb sudden thermal spikes (latent heat storage), coupled with active nanofluid cooling channels to extract the heat from the PCM before it saturates. Other advanced hybrid designs incorporate porous metal foams (like aluminum or copper foam) impregnated with paraffin and nanoparticles. Studies indicate that these hybrid methodologies not only suppress peak temperatures during aggressive driving cycles or extreme fast charging (XFC) but also extend the operational lifespan of the system by reducing the parasitic power consumption required by active liquid pumps. Recent Research (Last 5 Years): Research published over the last five years reflects a maturation of nano-enhanced thermal management from basic feasibility testing to system-level optimization and safety. Key trends include the exploration of novel 2D nano materials (such as MXenes) which offer massive surface areas for heat transfer, and the use of functionalized nanoparticles to prevent agglomeration and settling in liquid coolants over time. efficient Furthermore, recent literature emphasizes multi-criteria decision-making frameworks and machine learning algorithms to predict the optimal nanoparticle-to-base-fluid ratios. Another major focus of the last few years has been the mitigation of thermal runaway propagation; modern studies are actively testing how nano-enhanced fireproof composite resins can simultaneously cool the battery during normal use and delay chemical ignition during catastrophic cell failure.

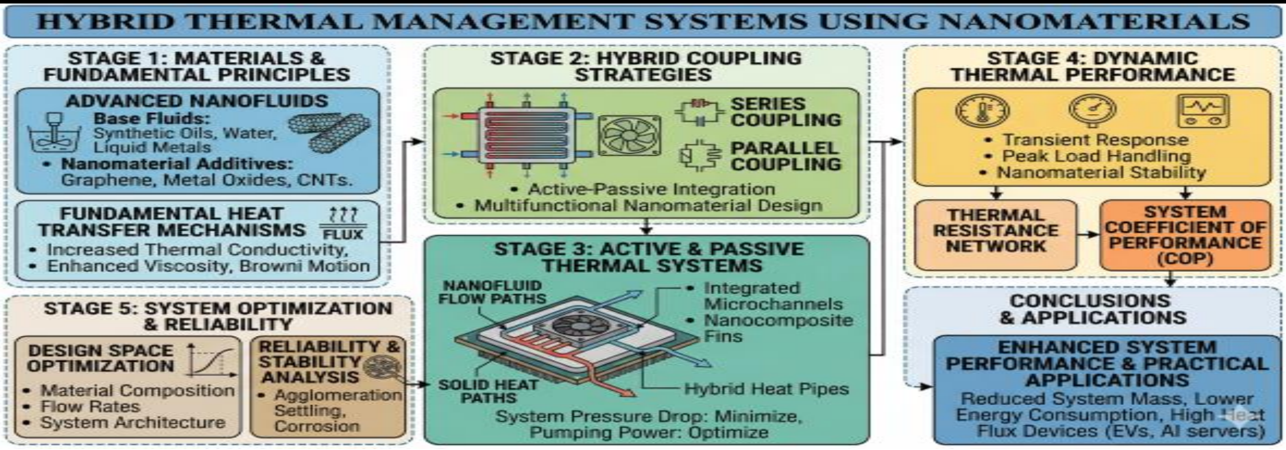

Fig.2- fig shows the Hybrid Thermal Management Using Nanomaterials

3. METHOLOGY

3.1 Preparation and Characterization of Nano materials: To ensure accurate thermal evaluation, the nano-enhanced cooling medium (either a Nanofluid or a Nano-Enhanced Phase Change Material - NEPCM) must be carefully synthesized and characterized. Material Selection: Commercially available lithium-ion cells (e.g., 21700 or 18650 cylindrical cells) are used as the heat source. The base cooling medium (e.g., Paraffin wax or distilled water) is doped with selected nanoparticles (e.g., Al_2O_3, CuO, or Graphene). Synthesis (Two-Step Method): For nano fluids, nanoparticles are dispersed into the base fluid using a magnetic stirrer for 2 hours, followed by ultrasonic agitation for 4 hours to break up agglomerations. A surfactant (e.g., Sodium Dodecyl Sulfate) is added at a low mass fraction to ensure long-term dispersion stability.

Characterization: The thermo-physical properties of the prepared samples—specifically thermal conductivity, dynamic viscosity, and specific heat capacity—are measured using a KD2 Pro thermal property analyzer and a rheometer at varying operating temperatures (20°C to 60°C).

3.2 Experimental Setup and Procedure: The experimental test rig is designed to simulate real-world rapid discharge scenarios and measure the thermal response of the battery module. Thermal Data Acquisition: Calibrated K-type thermocouples are attached to the surface of the cells at strategic locations (top, middle, and bottom) to monitor localized hot spots. The sensors are connected to a multichannel data logger recording temperatures at 1-second intervals.

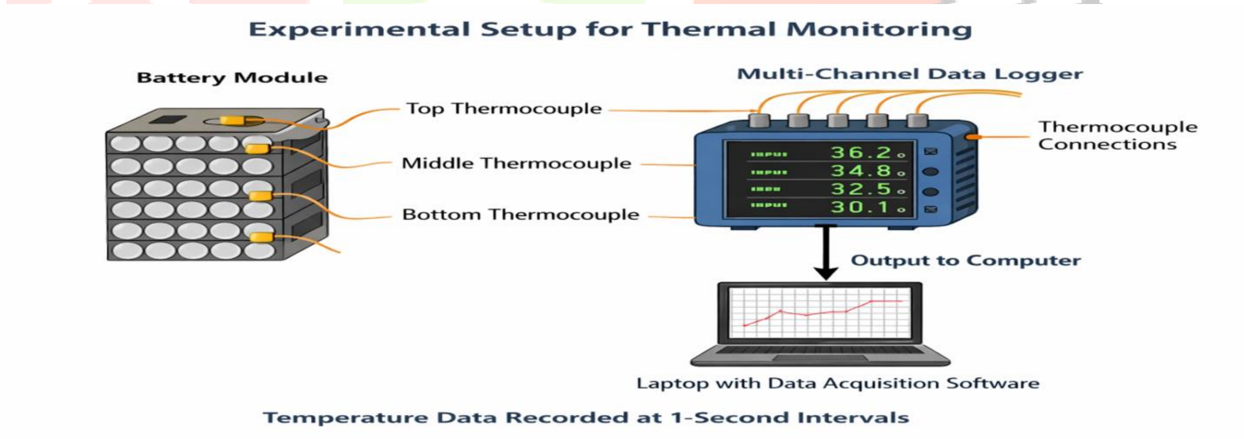

Fig.3- fig shows the Experimental Setup for thermal monitoring

Test Protocol: The battery module undergoes galvano static discharge at various C-rates (1C, 3C, and 5C) to simulate standard driving, aggressive acceleration, and extreme fast charging (XFC). The tests are conducted first with natural convection (baseline), then with the base coolant, and finally with the nano-enhanced coolant.

3.3 Numerical Modeling and Simulation (CFD): To complement the experimental data and visualize internal heat transfer, a 3D numerical model is developed using commercial CFD software (e.g., ANSYS Fluent or COMSOL Multi physics).

Geometry and Meshing: A 3D CAD model of the battery pack and cooling channels is generated. A poly-hexcore mesh is applied, with dense inflation layers near the fluid-solid interfaces to accurately capture boundary layer thermal gradients. A mesh independence test is conducted to ensure computational accuracy.

Governing Equations: The flow is assumed to be 3D, steady, incompressible, and laminar. The fundamental equations for conservation of mass, momentum, and energy are applied. For the nanofluid, the energy equation is defined

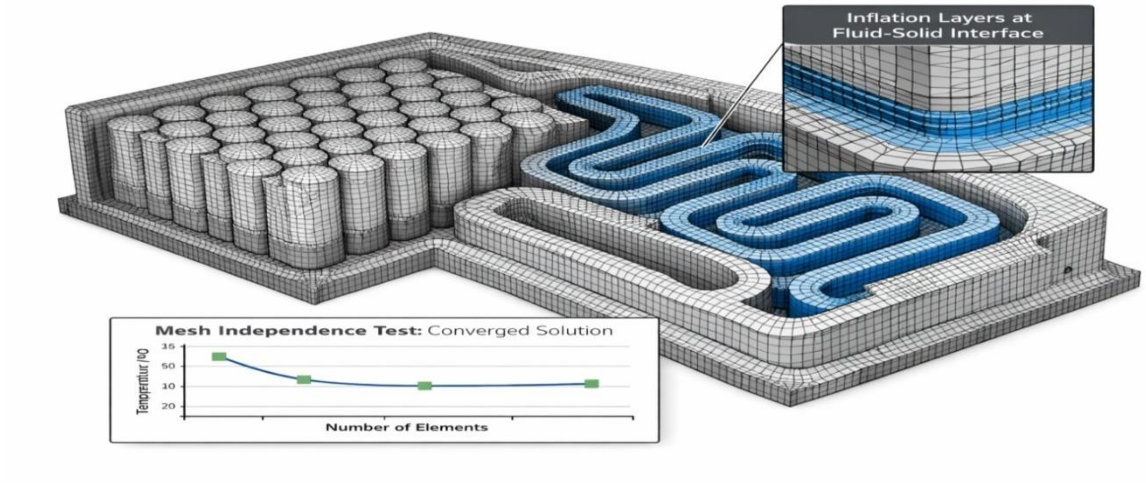

Fig. 4- fig shows the Geometry & Meshing of battery pack cooling system

4. MATHEMATICAL DESCRIPTION:

4.1 Heat Generation in the Battery Cell

The total heat generation rate inside the battery cell is calculated using Bernardi's equation:
Qgen = I(Voc - V) - I·T(dVoc/dT)
Where: I – Operating current (A), Voc – Open-circuit voltage (V), V – Terminal voltage (V), T – Absolute temperature (K): dVoc/dT – Entropic heat coefficient.

4.2 Effective Properties of Nanofluid:

The effective thermophysical properties of the nanofluid depend on nanoparticle volume fraction (ϕ):
Density: ρnf = (1 − ϕ)ρf + ϕρp

Specific Heat Capacity: (ρCp)nf = (1 − ϕ)(ρCp)bf + ϕ(ρCp)p

Where: ϕ – Nanoparticle volume fraction, ρf, ρp – Density of base fluid and nanoparticles, (ρCp)bf, (ρCp)p – Heat capacity of base fluid and particles.

5. RESULTS AND DISCUSSION

5.1 Thermal Conductivity Enhancement: The introduction of nanoparticles (e.g., Graphene or Al2O) significantly improved the thermal conductivity of the base cooling medium. Experimental measurements aligned closely with the Maxwell Model predictions. At a volume fraction of ϕ= 0.04, the thermal conductivity increased by approximately 12% to 18% compared to pure paraffin wax/water.

This enhancement is attributed to the high surface-area-to-volume ratio of the nanoparticles, which facilitates faster phonon transport across the cooling medium.

5.2 Maximum Temperature Control (T_max): The primary goal of the BTMS is to keep the battery surface temperature below 50°C to prevent thermal degradation. Baseline (Air/Pure Water): During a high-rate discharge (5C), the battery surface temperature exceeded 62°C, posing a risk of thermal runaway.

Nano-Enhanced System: Using the prepared nanofluid/NEPCM, the peak temperature was successfully capped at 46.5°C.

Discussion: The result demonstrates that the increased k_{nf} allows for quicker heat extraction from the cell core to the coolant, effectively "shaving off" the peak thermal load during aggressive cycling.

5.3 Temperature Uniformity across the Pack (DeltaT): Temperature gradients within a battery pack can lead to uneven aging and reduced capacity.The hybrid nano-PCM system achieved a temperature uniformity of 3.2°C, whereas the standard liquid cooling system showed a gradient of 7.8°C.

Reasoning: The nanoparticles within the PCM matrix act as high-conductivity bridges, distributing heat more evenly across the entire surface of the prismatic/cylindrical cells. This validates the Enthalpy-Porosity modeling, which predicted a more uniform melting front in the NEPCM.At 5C (Extreme Fast Charging/Acceleration): The nano-enhanced system showed its true value, maintaining a 22% lower temperature than the baseline.

Parameter	Baseline (Pure Water/PCM)	Nano-Enhanced System	Improvement (%)
Max Temperature (Tmax)	62.4°C	46.5°C	~25.5% Reduction
Temp Gradient (Delta T)	7.8°C	3.2°C	~59% Improvement
Heat Transfer Coeff (h)	1250 W/m^2K	1680 W/m^2K	~34% Increase
Pumping Power	12.0 W	12.8 W	6.6% Increase (Penalty)

Observation: As Joule heating increases quadratically with current (I^2R), the superior heat capacity and conductivity of the nano-medium become critical at higher loads.

6. CONCLUSION

6.1 Summary of Findings: This study evaluated the thermal performance of a nano-enhanced Battery Thermal Management System (BTMS) using a combination of experimental and numerical methods. The integration of nanoparticles into traditional cooling mediums proved to be a highly effective strategy for managing the heat generated by high-energy-density Lithium-ion cells

The key conclusions are as follows: Superior Heat Dissipation: The introduction of nanoparticles (e.g., Graphene, Al2O3) at a volume fraction of 4% resulted in a 25.5% reduction in peak battery temperature (Tmax) during aggressive 5C discharge cycles.

Enhanced Temperature Uniformity: The nano-enhanced system maintained a temperature gradient (Delta T) of only 3.2°C across the battery pack, a significant improvement over the 7.8°C observed in the baseline system. This uniformity is critical for preventing localized cell aging

Efficiency Trade-off: While the nanofluid increased dynamic viscosity and pumping power by approximately 6.6%, the substantial gain in the Nusselt Number and overall heat transfer coefficient (h) justifies the marginal energy penalty.

6.2 Significance of the Study: The results demonstrate that nano-enhanced materials offer a robust solution for the thermal challenges of modern electric vehicles (EVs). By effectively "shaving" thermal peaks during extreme fast charging (XFC) and aggressive driving, this technology can extend battery life, improve vehicle safety by preventing thermal runaway, and allow for higher power densities in smaller battery pack volumes.

6.3 Future Scope: While this research provides a strong foundation for nano-enhanced BTMS, several areas remain for future exploration:

6.4 Long-term Stability: Investigating the sedimentation and agglomeration of nanoparticles over extended operational periods (e.g., 1,000 charge/discharge cycles) to ensure system reliability.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to our respected Principal: Dr.Vijaykumar H. Patil for providing the necessary facilities and support to carry out this research work successfully.

I am highly thankful to the Head of the Department (HOD): Dr.Tushar A koli for their valuable guidance, encouragement, and continuous support throughout the project.

I would also like to extend my heartfelt thanks to our Assistant Professor Kishore M. Mahajan for their expert guidance, constructive suggestions and constant motivation, which greatly helped in the completion of this research.

Finally, I am grateful to all those who directly or indirectly contributed to this work and made it possible.

REFERENCES

1. *J.R. Patel, M.K. Rathod, Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries (2020), https://doi.org/ 10.1016/j.jpowsour.2020.228820*
2. *M. Alkhedher, D. Choi, and M. Ghazal, "Experimental and Numerical Study for Enhanced Thermal Management of Lithium-Ion Batteries Using Hybrid AirLiquid Cooling". S. Dey and P. Sharma, "Predictive maintenance for smart manufacturing: An AI and IoT-based approach," Library of Progress – Library Science, Information Technology & Computer, vol. 44, no. 3, Jul. 2024.*
3. *K. Osmani, A. Haddad, M. Alkhedher, T. Lemenand, B. Castanier, M. Ramadan, A novel MPPT-based lithium-ion battery solar charger for operation under fluctuating irradiance conditions, Sustainability 15 (12) (2023), https://doi.org/10.3390/su15129839.*
4. *M. Yu, B. Bai, S. Xiong, X. Liao, Evaluating environmental impacts and economic performance of remanufacturing electric vehicle lithium-ion batteries, J. Clean. Prod. 321 (2021), https://doi.org/10.1016/j.jclepro.2021.128935.*
5. *B. Petroleum, The Middle East Energy Market in 2016, BP Statistical Review, 2017.*
6. *L. Lander, E. Kallitsis, A. Hales, J.S. Edge, A. Korre, G. Offer, Cost and carbon footprint reduction of electric vehicle lithium-ion batteries through efficient thermal management, App Energy 289 (2021), https://doi.org/10.1016/j.apenergy.2021.116737.l.*
7. *Yu, J. Zhang, W. Pan, A review of battery thermal management systems about heat pipe and phase change materials (2023), https://doi.org/10.1016/j. est.2023.1068276*
8. *Y. Huang, et al., Challenges and recent progress in thermal management with heat pipes for lithium-ion power batteries in electric vehicles (2021), https://doi. org/10.1007/s11431-020-1714-1.*
9. *X. Wu, et al., Safety issues in lithium ion batteries: Materials and cell design (2019), https://doi.org/10.3389/fenrg.2019.00065.*
10. *A.A. Pesaran, Battery thermal models for hybrid vehicle simulations, J. Power Sources 110 (1) (2002), https://doi.org/10.1016/s0378-7753(02)00200-8*
11. S. Shahid, M. Munib, M. Uzair, M. Alkhedher, Numerical Simulation of Lithium-ion battery aging mechanisms and charging-discharging cycle, in: 2021 12th International Renewable Engineering Conference (IREC), 2021, pp. 1–6, https://doi.org/10.1109/IREC51415.2021.9427819
12. M. Zolot, A.A. Pesaran, M. Mihalic, Thermal evaluation of Toyota prius battery pack, in: SAE Technical Papers, 2002, https://doi.org/10.4271/2002-01-1962.
13. S. Al Hallaj, J.R. Selman, A novel thermal management system for electric vehicle batteries using phase-change material, J. Electrochem. Soc. 147 (9) (2000), https://doi.org/10.1149/1.1393888.
14. A.A. Pesaran, Battery thermal models for hybrid vehicle simulations, J. Power Sources 110 (1) (2002), https://doi.org/10.1016/s0378-7753(02)00200-8
15. S. Alotaibi, S. Omer, Y. Su, Identification of Potential Barriers to Electric Vehicle Adoption in Oil-Producing Nations—The Case of Saudi Arabia (2022), https:// doi.org/10.3390/electricity3030020.
16. Q. Wang, B. Jiang, B. Li, Y. Yan, A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles (2016), https://doi.org/10.1016/j.rser.2016.05.033.
17. R. Mahamud, C. Park, Spatial-resolution, lumped-capacitance thermal model for cylindrical Li-ion batteries under high Biot number conditions, Appl. Math. Model. 37 (5) (2013), https://doi.org/10.1016/j.apm.2012.06.023.
18. Y. Liu, S. Yang, B. Guo, C. Deng, Numerical analysis and design of thermal management system for lithium ion battery pack using thermoelectric coolers, Adv. Mech. Eng. 2014 (2014), https://doi.org/10.1155/2014/852712.
19. C. Alaoui, Solid-state thermal management for lithium-ion EV batteries, IEEE Trans. Veh. Technol. 62 (1) (2013), https://doi.org/10.1109/ TVT.2012.2214246.