

Numerical Analysis of Electric Vehicle Battery Thermal Management using Nanofluid of Varying Concentrations

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Abstract - Due to temperature sensitivity of lithium-ion batteries, thermal management is required for their optimal performance in electric vehicles. Nanofluids can be an effective alternative in place of conventional liquid coolants. Graphene oxide nanoparticles inside deionized water as base fluid were used to test the convective heat transfer rate and pressure drop across an electric vehicle battery cooling module. The flow rates across the module were varied for flows within a range of 3000 to 5000 Reynolds number. It was found that the cooling rates are sensitive to Reynolds number, type of coolant and nanoparticle fraction inside the base fluid. The findings were validated against data available in literature and the proposed cooling module was studied for overall thermal performance. It was found that for high Reynolds number of 5000, a superior Thermal Performance Factor (TPF) of 1.1 was obtained and the increase in thermal performance was not linearly correlated to the increase in Reynolds Number.

Keywords: Battery Thermal Management System (BTMS), Lithium-ion battery cooling, Electric vehicle battery, Nanofluid

1. Introduction

The use of fossil fuels as the primary energy source in many applications has not only led to the depletion of natural reserves but it also comes at a significant cost to the environment due to the accompanying emissions from combustion. The ever-increasing global energy demand needs to be quenched from alternative cleaner modes of energy production. Transportation sector is a major contributor to fossil fuel related emissions and there has been a conscious effort to shift from petroleum operated vehicles to electric vehicles. This has the potential to significantly dent the carbon footprint of transport vehicles across the globe.

Energy storage devices of various chemical compositions in the form of sodium-sulphur, nickel-iron, lead-acid, and lithium-ion are used for engineering applications [1]. However, Li-ion (Lithium-ion) batteries are the preferred source of energy storage for EV's (Electric Vehicles) due to their longer life span, high power density, fast charging, and high discharge permissibility [2]. Due to the electrochemical processes inside these Li-ion batteries, they are prone to generating large amounts of localized heat. If this heat is not properly removed, it can significantly affect the life of batteries and lead up to thermal runaway [3],[4]. This is especially true for cascaded Li-ion battery banks where thermal runaway inside one battery can easily propagate heat across other batteries causing ignition and even lead to explosive reactions [5]. In some cases, high temperatures inside the Li-ion batteries can also result in polarization heating, short circuit, and separator breakdown [6], which can all shorten the overall lifespan of the battery [7]. Therefore, thermal management system for such devices is of great importance, not only for optimum performance but also for overall safety of the equipment [8].

Heat is being continuously generated inside Li-ion batteries during the charging and discharging phases due to electrochemical reactions [9]. Therefore, due to the nature of their operation, this unchecked increase can have disastrous consequences for battery health. A Li-ion battery is made up of a cathode-anode, an electrolyte, and a separator. During the first charge phase, a thin passivation layer develops on the carbon anode's surface providing a strong electrolyte contact which keeps the response rate of the battery stable. The optimum operating temperature for Li-ion batteries has been shown to be in the range of 15-35°C [10]. While such external temperatures are usually common across the globe, however in certain

conditions the temperatures can vary significantly [11]. Any temperature above or below this limit can lead to “thermal abuse” of the Li-ion battery. Therefore, any effective battery thermal management system must be able to provide stable surface temperatures within the acceptable operating range of the battery [12]. Direct cooling methods can be used for such applications; however, such cooling can also cause a thermal shock [13]. Air cooling is usually employed for cooling of this type of batteries [14]; however, air cooling is not suitable in case of high heat flux applications [15] and liquid cooling is the preferred method for such applications [16] due to their high heat transfer rates and low power consumption. Liquid coolants have also found applications in certain commercial vehicles of automotive brands such as Porsche and Tesla [17]. Additionally, the design of cooling systems for battery thermal management should be such that it is compact, and no significant temperature gradient should exist between adjacent cells [18]. Optimization of cooling channels [19] and the use of alternative coolants have been identified as two possible methods of improvement for cooling rates across such systems.

Nanofluids are a highly efficient alternative to conventional coolants used for such applications [20]. They are particle suspensions derived by introducing nanoparticles inside base fluids to improve the heat transfer coefficient of cooling fluids [21]. Aluminium oxide [22][23], copper oxide [24], graphene oxide [25] and zirconia nanofluids [26][27] have been studied to determine the superior cooling effects of nanofluids. Geometric modifications were applied by Naqvi et al. to enhance the cooling rates and it was found that passive mixing combined with corrugation patterns provides increased cooling rates across cooling channels [28]. Li et al. [29] found that increased pressure losses accompany the convective heat transfer enhancement from nanofluids. Dean vortices are generated across wavy channels that promote fluid mixing and enhanced heat transfer, which can be combined with secondary corrugations to improve overall thermal performance. Therefore, for applications where improved heat transfer rates are necessary, nanofluids coupled with secondary mixing can be an alternative solution, especially in cases when the pumping requirements are not the limiting factor.

The review of available literature suggests that effective thermal management of batteries is critical to their performance as energy storage devices. However, the conventional coolants can no longer meet the cooling requirements of such devices. The use of nanofluids as coolants presents a promising approach to heat transfer enhancement especially when coupled with passive mixing, which occurs naturally inside wavy channels. Therefore, the present study aims to improve the performance of battery thermal management systems using passive mixing of graphene oxide nanofluids inside wavy battery cooling channels.

2. Methodology

The cells in an 18650-type Li-ion battery pack are placed in parallel straight lines, therefore a model of the cooling channels within the side space of a battery module with 444 cells having a side inlet and outlet, as shown fig. 1, was developed using SolidWorks. The cooling channel had a naturally wavy structure due to the circular curvature of cells inside the battery pack which provides a good layout for fluid mixing inside the channels. The channels were oriented in a U-type layout which ensures continuous flow of nanofluid across the channels through the battery pack.

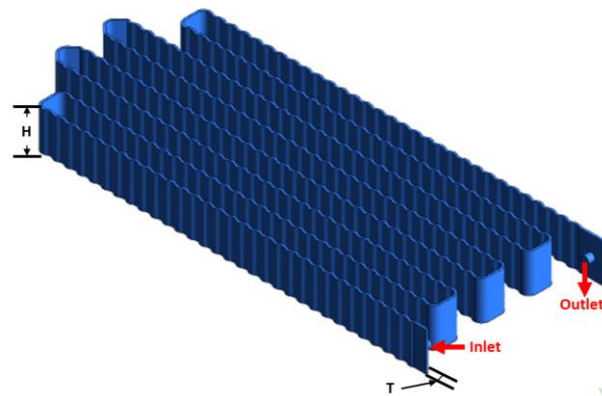


Fig. 1: Geometry of cooling channel.

The height of the cooling channel was fixed according to the height of the cells in battery pack and the specifications of the model are given in table 1.

Table 1: Geometric parameters.

S. No.	Geometric parameters	Values(mm)
1	Distance of cells in EV battery	1.5
2	Channel Thickness, t	3
3	Cell Diameter	18
4	Wall Thickness	0.5
5	Channel Height for Cooling, H	63
6	Port Diameter at Inlet, D	12

2.1. Assumptions

The numerical model developed for conjugate heat transfer was assumed to have the following characteristics.

- Fluid incompressibility
- Steady State heat transfer across the solid and fluid domains
- Negligible radiation and channel surface effects
- Negligible viscous heating

2.2. Governing Equations

The governing equations for the case can be expressed [28] as follows:

$$\nabla \cdot (\rho \mathbf{V}) = 0 \quad (1)$$

$$\mathbf{V} \cdot \nabla (\rho \mathbf{V}) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{V}) \quad (2)$$

$$\mathbf{V} \cdot \nabla (\rho C_p T_f) = \nabla \cdot (K_f \nabla T_f) \quad (3)$$

$$\nabla \cdot (k_s \nabla T_s) = 0 \quad (4)$$

2.3. Numerical Method

The numerical calculations using SIMPLEC algorithm, and a second order upwind discretization were performed for a turbulent flow regime between 3000 to 5000 Reynolds number using a velocity inlet and pressure outlet. A no slip boundary was applied to the walls with a heat flux of 3.33 kW/m². A hexahedral non uniform mesh, given in fig. 2 was generated for the model with a side length of 0.9mm for each element.

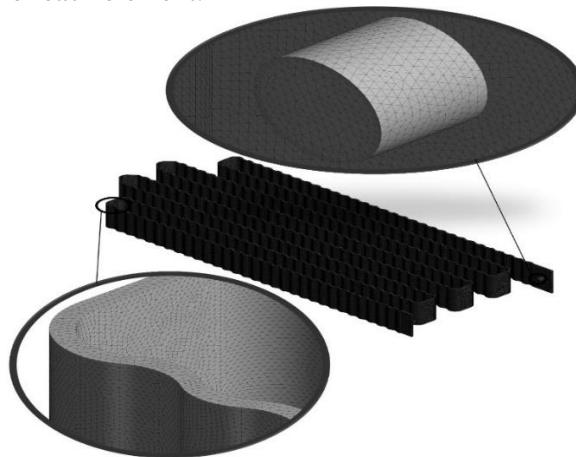


Fig. 2: Meshing of cooling channel.

Water was chosen as the initial coolant, however the cooling effects of adding graphene oxide nanoparticle fractions to water as base fluid were studied. The properties of resulting mixture were calculated using well established relations for such mixtures available in literature and the properties are given in table 2.

Table 2: Coolant properties.

S. No.	Nanoparticles Concentration	Specific heat J/kg K	Viscosity mPa.s	Density kg/m ³	Thermal Conductivity W/m. K
1	0 % (Pure Water)	4142	0.829	995.50	0.611
2	0.025 %	4123	0.844	995.60	0.636
3	0.075 %	4096	0.868	995.80	0.681
4	0.10 %	4080	0.885	995.90	0.708

2.4. Parametric Relations

Pressure drop is a critical parameter for this type of heat exchanger and can be expressed in terms of dimensionless friction factor. The fanning friction factor is given in the following relation.

$$f = \frac{\Delta P D_h}{2 \rho v^2 L} \quad (5)$$

The convective heat transfer rates were determined using Nusselt number as the evaluating dimensionless parameter. The heat transfer coefficient was calculated using the inlet and outlet temperatures obtained from the numerical calculation.

$$h = \frac{q}{\left(T_w - \left(\frac{T_{inlet} + T_{outlet}}{2} \right) \right)} \quad (6)$$

$$Nu = \frac{h D_h}{k_{fl}} \quad (7)$$

The thermal performance factor given by Harikrishnan [30] was used for evaluation of overall design.

$$TPF = \frac{Nu/Nu_o}{(f/f_o)^{1/3}} \quad (8)$$

3. Results and Discussion

A grid independence was initially performed at progressively smaller element sizes until stable results were achieved irrespective of the grid size. The mesh was refined from very coarse to fine until further decrease in element size provided negligible change in results. Once the mesh was refined up to approximately 15 million elements the numerical error dropped to less than 1% as shown in table 3.

Table 3: Grid Independence.

Number of elements	Mesh Status	Maximum Temperature (K)	% Error
2535248	Very coarse	311.1	
6934169	Coarse	327.3	5.2%
10264945	Fine	339.1	3.6%
13845367	Very fine	342.5	1.0%
15728603	Very fine	342.7	0.1%

The results were validated against the study by Wiriyasart [31] to establish the validity of numerical solution for the present study. The obtained temperatures were slightly lower, as shown in fig. 3, signifying a minor underprediction, however the results were well within acceptable range of numerical error.

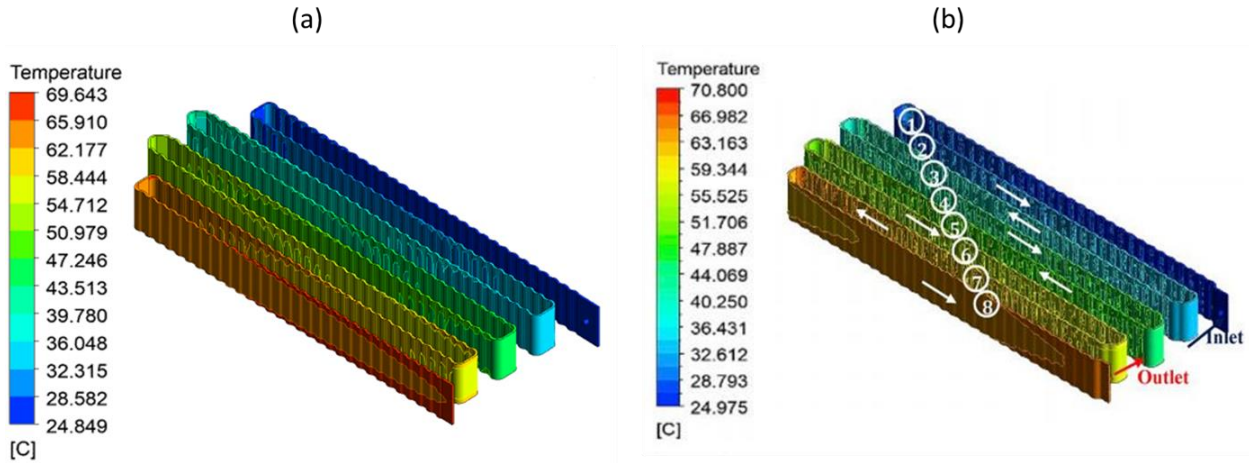


Fig. 3: a) CFD, b) Wiriyasart [31] at 0.2m/s

It was found that adding graphene oxide nanoparticles inside deionized water extracts more heat from the walls of the battery as compared to pure deionized water. However, this increase in nanoparticle concentrations leads to higher pressure drops, which is directly proportional to the increase in Reynolds number as shown in fig. 4a. The friction factor decreases with the increase in Reynolds number with 0.1658 occurring at 5000 Reynolds number. This reduced value means that the fluid bears less friction and can also transport more energy across the cooling channels.

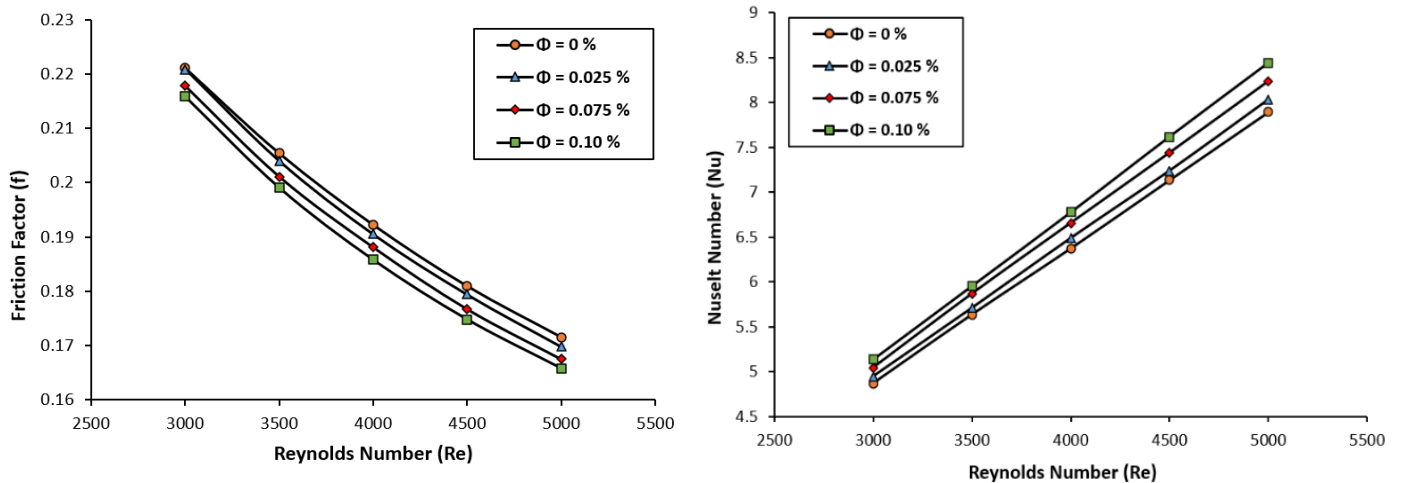


Fig. 4: a) friction factor at increasing Reynolds number, b) Nusselt number at increasing Reynolds number.

As shown in fig. 4b, the increase in Nusselt number correlates almost linearly with increase in Reynolds number, showing the increase in heat transfer rates at higher flow rates. The highest Nusselt number value of 8.4394 was achieved for 0.1% nanofluid concentration at a Reynolds number of 5000. However, the increase in nanoparticle concentration is accompanied by increase in overall pressure drop and the lowest pressure drop is observed for pure water flow across the channels.

The fig. 5 shows that the battery surface temperature decreases by up to 0.4% for very small increase of 0.1% in nanoparticle concentration across the operating fluid. Therefore, the cooling advantage achieved with this method is

significant and can be extremely useful for applications of high heat flux which requires efficient cooling fluids. The cooling effects are even more significant with the increase in Reynolds number which occurs due to the mixing effects that become more effective at high Reynolds numbers.

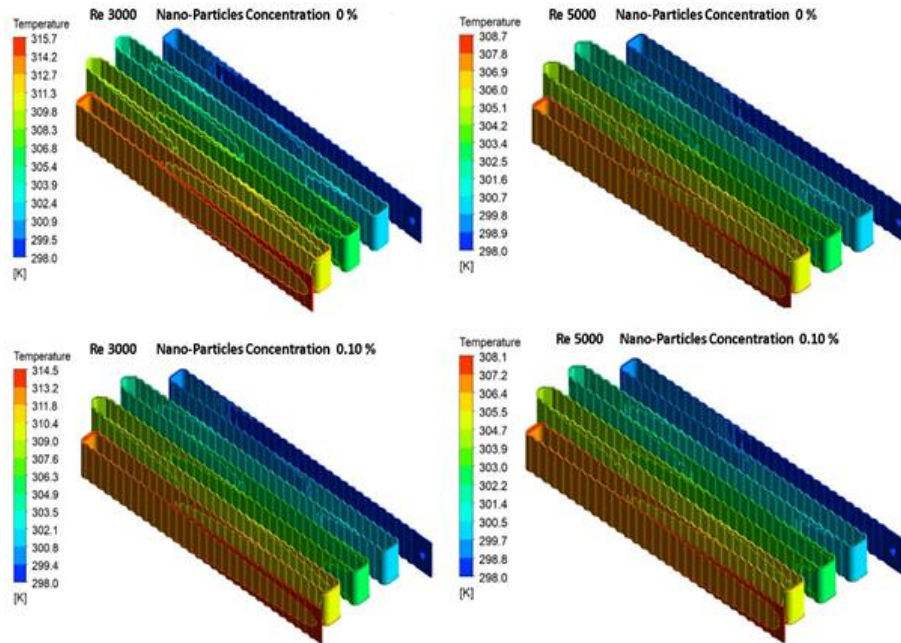


Fig. 5: Temperature Contours at 3000 and 5000 Reynolds number

The overall thermal performance factor (TPF) for varying nanoparticle concentrations was plotted against the increase in Reynolds number. It was observed that for higher concentrations of nanoparticles the increase in heat transfer rate outperforms the pressure drop particularly at high Reynolds number. Therefore, this model is especially useful at high Reynolds numbers where the heat transfer benefits are significant.

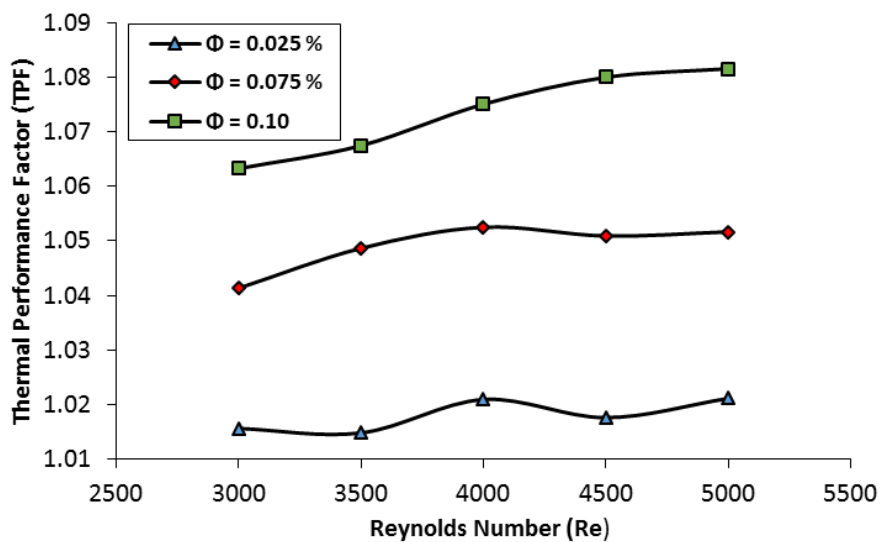


Fig. 6: Thermal Performance Factor

4. Conclusion

Due to high energy density of Li-ion batteries, appropriate thermal management is necessary for efficiency, life, and safety of the battery. The limited space in the battery packs requires compact and efficient cooling systems. However, since conventional coolants no longer seem to provide the required convective heat transfer rates therefore, the use of nanofluids for such applications is very promising. These coolants provided superior performance at higher Reynolds numbers due to the fluid mixing that occurs across the curved channels in the battery packs such as the one utilized in present study. The increase in TPF demonstrates that at higher Reynolds numbers the increase in heat transfer can make up for the increase in pressure drop.

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References

1. Yudhistira R, Khatiwada D, Sanchez F (2022) A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage. *J Clean Prod* 358:131999
2. Zhao S, Guo Z, Yan K, Wan S, He F, Sun B, Wang G (2021) Towards high-energy-density lithium-ion batteries: Strategies for developing high-capacity lithium-rich cathode materials. *Energy Storage Mater* 34:716–734
3. Bibin C, Vijayarajam M, Suriya V, Sai Ganesh R, Soundarraj S (2020) A review on thermal issues in Li-ion battery and recent advancements in battery thermal management system. *Mater Today Proc* 33:116–128
4. Pargoletti E, Arnaboldi S, Cappelletti G, Longhi M, Meroni D, Minguzzi A, Mussini PR, Rondinini S, Vertova A (2022) Smart interfaces in Li-ion batteries: Near-future key challenges. *Electrochim Acta* 415:140258
5. Ogunfuye S, Sezer H, Said AO, Simeoni A, Akkerman V (2022) An analysis of gas-induced explosions in vented enclosures in lithium-ion batteries. *J Energy Storage* 51:104438
6. Ren D, Feng X, Liu L, Hsu H, Lu L, Wang L, He X, Ouyang M (2021) Investigating the relationship between internal short circuit and thermal runaway of lithium-ion batteries under thermal abuse condition. *Energy Storage Mater* 34:563–573
7. Liu K, Ashwin TR, Hu X, Lucu M, Widanage WD (2020) An evaluation study of different modelling techniques for calendar ageing prediction of lithium-ion batteries. *Renewable and Sustainable Energy Reviews* 131:110017
8. Jaguemont J, Van Mierlo J (2020) A comprehensive review of future thermal management systems for battery-electrified vehicles. *J Energy Storage* 31:101551
9. Shahjalal M, Shams T, Islam MdE, Alam W, Modak M, Hossain S Bin, Ramadesigan V, Ahmed MdR, Ahmed H, Iqbal A (2021) A review of thermal management for Li-ion batteries: Prospects, challenges, and issues. *J Energy Storage* 39:102518
10. Qi X, Sajadi SM, Mahmoud MZ, Li Z, Shamseldin MA, Aybar HŞ (2022) Study of circular, horizontal and vertical elliptical enclosures filled with phase change material in thermal management of lithium-ion batteries in an air-cooled system. *J Energy Storage* 53:105041
11. Piao N, Gao X, Yang H, Guo Z, Hu G, Cheng H-M, Li F (2022) Challenges and development of lithium-ion batteries for low temperature environments. *eTransportation* 11:100145
12. Liang L, Zhao Y, Diao Y, Ren R, Jing H (2021) Inclined U-shaped flat microheat pipe array configuration for cooling and heating lithium-ion battery modules in electric vehicles. *Energy* 235:121433
13. Zhou Z, Zhou X, Cao B, Yang L, Liew KM (2022) Investigating the relationship between heating temperature and thermal runaway of prismatic lithium-ion battery with LiFePO₄ as cathode. *Energy* 256:124714
14. Li X, Zhou Z, Zhang M, Zhang F, Zhou X (2022) A liquid cooling technology based on fluorocarbons for lithium-ion battery thermal safety. *J Loss Prev Process Ind* 78:104818
15. Fan Z, Fu Y, Liang H, Gao R, Liu S (2023) A module-level charging optimization method of lithium-ion battery considering temperature gradient effect of liquid cooling and charging time. *Energy* 265:126331

16. Akbarzadeh M, Kalogiannis T, Jin L, Karimi D, Van Mierlo J, Berecibar M (2022) Experimental and numerical thermal analysis of a lithium-ion battery module based on a novel liquid cooling plate embedded with phase change material. *J Energy Storage* 50:104673
17. He L, Gu Z, Zhang Y, Jing H, Li P (2023) Review on Thermal Management of Lithium-Ion Batteries for Electric Vehicles: Advances, Challenges, and Outlook. *Energy and Fuels* 37:4835–4857
18. Rao Z, Wang S (2011) A review of power battery thermal energy management. *Renewable and Sustainable Energy Reviews* 15:4554–4571
19. Gao R, Fan Z, Liu S (2022) A gradient channel-based novel design of liquid-cooled battery thermal management system for thermal uniformity improvement. *J Energy Storage* 48:104014
20. Shang X shuo, Li Q wen, Cao Q, Li Z rui, Shao W, Cui Z (2023) Mathematical modeling and multi-objective optimization on the rectangular micro-channel heat sink. *International Journal of Thermal Sciences*. <https://doi.org/10.1016/j.ijthermalsci.2022.107926>
21. Azodinia M, Mudabbir M, Karimipour A (2023) Numerical investigation of two-phase Al₂O₃ nanofluid in a microchannel equipped with bump through slip flow. *Eng Anal Bound Elem* 155:1028–1034
22. Zeng X, Yu H, He T, Mao N (2022) A Numerical Study on Heat Transfer Characteristics of a Novel Rectangular Grooved Microchannel with Al₂O₃/Water Nanofluids. *Energies (Basel)*. <https://doi.org/10.3390/en15197187>
23. Khan MZU, Younis MY, Akram N, Akbar B, Rajput UA, Bhutta RA, Uddin E, Jamil MA, García Márquez FP, Zahid F Bin (2021) Investigation of heat transfer in wavy and dual wavy micro-channel heat sink using alumina nanoparticles. *Case Studies in Thermal Engineering* 28:101515
24. Tiwari AK, Chatterjee K, Deolia VK (2023) Application of Copper Oxide Nanofluid and Phase Change Material on the Performance of Hybrid Photovoltaic–Thermal (PVT) System. *Processes*. <https://doi.org/10.3390/pr11061602>
25. Tariq H, Sajjad R, Ullah Khan MZ, Ghachem K, Naqvi AA, Khan SU, Kolsi L (2023) Effective waste heat recovery from engine exhaust using fin prolonged heat exchanger with graphene oxide nanoparticles. *Journal of the Indian Chemical Society* 100:100911
26. Alktranee M, Shehab MA, Németh Z, Bencs P, Hernadi K (2023) Effect of zirconium oxide nanofluid on the behaviour of photovoltaic–thermal system: An experimental study. *Energy Reports* 9:1265–1277
27. Khan MZU, Uddin E, Akbar B, Akram N, Naqvi AA, Sajid M, Ali Z, Younis MY, Márquez FPG (2020) Investigation of heat transfer and pressure drop in microchannel heat sink using al₂o₃ and zro₂ nanofluids. *Nanomaterials* 10:1–30
28. Naqvi, A.A.; Uddin, E.; Khan, M.Z.U. Passive Mixing and Convective Heat Transfer Enhancement for Nanofluid Flow across Corrugated Base Microchannels. *Energies* **2023**, *16*, 7893. <https://doi.org/10.3390/en16237893>
29. Li C, Huang J, Shang Y, Huang H (2020) Study on the flow and heat dissipation of water-based alumina nanofluids in microchannels. *Case Studies in Thermal Engineering*. <https://doi.org/10.1016/j.csite.2020.100746>
30. Harikrishnan S, Tiwari S (2019) Heat transfer characteristics of sinusoidal wavy channel with secondary corrugations. *International Journal of Thermal Sciences* 145:105973
31. Wiriyasart S, Hommalee C, Sirikasemsuk S, Prurapark R, Naphon P (2020) Thermal management system with nanofluids for electric vehicle battery cooling modules. *Case Studies in Thermal Engineering* 18:100583