INFLUENCE OF VENTILATION PLACEMENT ON THE COOLING EFFICIENCY OF LITHIUM-ION BATTERIES UNDER FORCED AIRFLOW CONDITIONS

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Article history
Received
14th June 2024
Revised
30th September 2024
Accepted
12th November 2024
Published
29th December 2024

ABSTRACT

In line with a rise in demand for lithium-ion batteries (LIBs) around the globe, LIB thermal management optimization is desirable. Moreover, the temperature rise of LIBs while discharging and charging affects their degradation and thermal runaway. The objective of this study is to investigate cooling performance in LIBs due to battery pack ventilation configuration. In this study, twenty 18650 lithium-ion cells (in 10S2P configuration) were simulated in Altair HyperWorks CFD - AcuSolve. The analysis provides a significant finding for the best thermal management approach by Design 2 with the position of an inlet at the top and outlet at the bottom of the battery pack, indirectly promoting uniform temperature distribution across the pack and avoiding local hot spots. These findings contribute significant insights into the effect of battery ventilation configuration for enhancing lithium-ion cooling performance.

Keywords:*Lithium-ion battery, Air cooling, Thermal management*

1.0 INTRODUCTION

Lithium-ion batteries (LIBs) have become dominantly used as a main power source in various electronic devices, electric cars, and renewable energy storage systems due to the capacity of high energy density and long cycles [1], [2]. In electric vehicles, lithium-ion cells are arranged in modules and combined into a battery pack, containing thousands of lithium-ion cells in a single pack. Due to the high demand for high performance and longer driving ranges in the market, the capacity of battery packs has been increased, leading to a higher number of lithium-ion cells. Numerous lithium-ion cells packed in battery packs result in excessive heat generation during the discharge and charge processes of electric car operation. However, lithium-ion batteries are sensitive to temperature, which affects their degradation, lifespan, and safety. With the increase in generated heat, the demand for a battery thermal management system is required to ensure the battery pack temperature remains within the optimal range of 20°C to 40°C [3]. As these technologies evolve, the optimization of thermal management for LIBs needs more extensive approaches to providing better solutions and has become a crucial field of research. Optimizing structure and temperature control not only improves the efficiency and durability of batteries but also reduces the potential dangers related to thermal runaway incidents [4]–[9]. However, the factors influencing the degradation and thermal safety of lithium-ion batteries remain significant in the development of LIBs for electric vehicles. The cells of a LIB pack become inefficient at 40°C, which may cause the entire battery pack to become unpredictable [10]–[15].

An effective approach to improving thermal management in LIBs is to focus on the design and array designs of the battery cells within a pack [16]–[18]. Out of these several arrangements, the staggered structure has received considerable interest since it has the potential to enhance both the distribution of temperature and the dynamics of airflow within the battery pack. In a previous study, Cho et al. (2014) studied the influence of environmental temperature on the cooling system's efficiency. Comparing the environmental temperature variation, the temperature is more uniform at high temperatures and behaves with lower temperature distribution at lower ambient temperatures. The cell position showed a significant impact where cells closer to the inlet reported lower maximum temperatures than cells located closer to the outlet, which specified proper cell configuration could improve the cooling and reduce the independent of the surrounding temperature. The position of the air inlet and outlet in the battery pack can affect the temperature distribution and airflow. The battery pack is made of Lithium Iron Phosphate (LFP) cells, and the position of the inlet at the top and outlet placed at the bottom of the battery pack indicated air is more restricted at the center of the cell. Most temperature gradients were also seen near the head of the pack, where airflow was nearly stagnant because of flow separation from the entrance plenum [19].

The addition of ventilation features would greatly improve the distribution and convective flow of the battery air cooling system. Proper ventilation allows hot air from inside the battery enclosure to be replaced by cooler ambient air which helps convection of heat. This exchange acts as a temperature control mechanism in the battery pack which directly helps to reduce heat rise mitigating thermal runaway and overall safety [20]. In normal operating in electric vehicles (EVs), usually batteries are subjected to varying loads and environmental conditions, and therefore efficient ventilation is important to maintain optimal operating temperatures.

Moreover, the configuration of cells showed a significant impact in improving the thermal management in the lithium-ion battery pack. The staggered cell configuration has disclosed beneficial thermal distribution and can improve thermal control strategies. In addition, the distribution airflows using staggered configuration reduce the hot spots and balance the heat distribution which results in enhanced cooling efficiency and reduced temperature variation across battery cells [21]–[24]. Research on the cell configuration explored by Yang et al. (2015) showed a similar effect of uniform temperature patterns and diminishing hotspots within battery assemblies. Throughout these findings, the geometric cell arrangements exposed influence factors for the improvement of effective thermal management in lithium-ion batteries [21]. Preventing temperature over the optimal temperature is important to maintain the cell efficiency and risk of thermal runaway. By properly monitoring the airflow characteristics, the battery performance can be operated at optimal efficiency [12], [25]. Furthermore, studies by Lu et al. have investigated the influence of various cooling techniques by evaluating battery performances, such as airflow distribution, the distribution of battery temperature consistency, and heat dissipation efficacy [26], [27].

Although numerous studies have examined various aspects of thermal management in lithium-ion batteries, there is a notable research gap in the comprehensive analysis of different ventilation design configurations, specifically concerning the placement of inlets and outlets and their impact on temperature distribution and airflow characteristics. This study aims to fill this gap by providing a detailed investigation of these design parameters under different operational conditions, offering valuable guidance for the development of more efficient thermal management systems. The study was conducted using a Computational Fluid Dynamic (CFD) approach by utilizing Altair HyperWorks CFD - AcuSolve. The CFD study simulates the airflow characteristic and temperature distribution within the cell and provides a comprehensive understanding of maintaining optimal temperature in the battery pack. The simulation is limited to steady-state conditions and the volume of fluid (air) in the battery pack is chosen as the CFD domain. In addition, the study focused on the temperature and airflow pattern at the mid-plane of the cell. In general, these findings have the potential to enhance performance, extend lifespan, and enhance the safety of lithium-ion battery packs in various applications.

2.0 METHODOLOGY

2.1 Battery Model Development

A total of 20 cells of 18650 lithium-ion are utilized in the construction of a battery pack. To create a pack that effectively satisfies the load demands of an electric bike, the battery pack employed a 10S2P configuration, which combines both series and parallel connection, to produce a battery pack with an output voltage of 37 V and a capacity of 4.4 Ah. The cooling of the battery is performed using forced air cooling that blows the airspeed at 0.9 m/s to the inlet of the battery pack is set to ambient condition.

2.2 Geometry Preparation

Modeling was conducted on 20 of 18650 lithium-ion batteries using commercial CAD and Altair HyperWorks CFD - AcuSolve to perform flow and thermal analysis for the battery pack. The dimensions of the 18650 batteries are uniform across all setups. Figure 1 illustrates three distinct ventilation designs for a battery casing used in cooling 18650 lithium-ion batteries with air. In Design 1, the inlet and outlet are positioned on opposite sides of the casing, allowing airflow to move directly through the batteries in a straight path. Design 2 places the inlet on the top side of the casing and the outlet on the opposite bottom side, causing air to flow diagonally through the battery pack. This diagonal flow path could enhance the cooling of centrally located batteries as it better penetrates the middle section. However, batteries near the inlet and outlet may experience slightly different cooling rates due to this flow path. Design 3 positions both the inlet and outlet on the different sides, promoting air circulation within the casing before exiting. This design encourages recirculation, potentially enhancing the cooling of batteries located further from the inlet and outlet, leading to a more uniform temperature distribution.

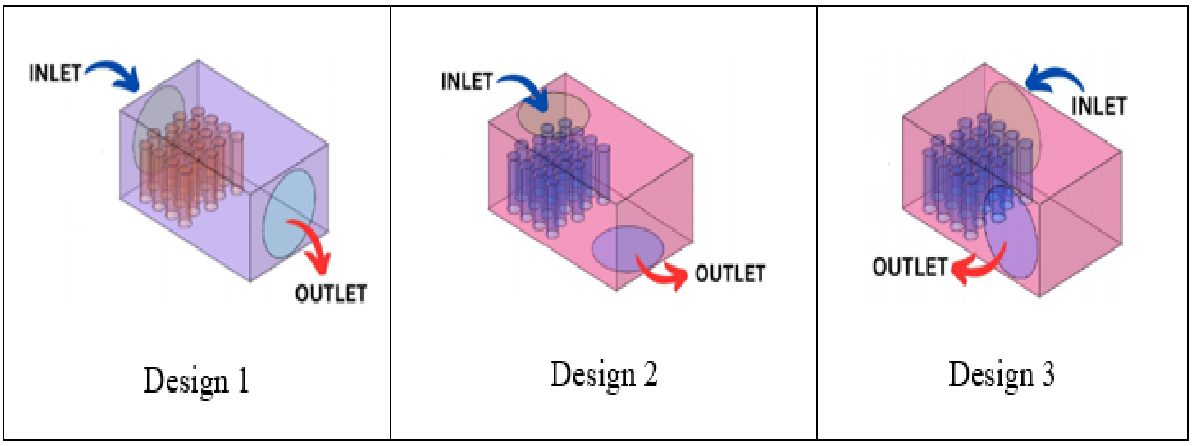

Figure 1: Ventilation design configuration

2.3 Meshing

The global parameters for the CFD domain are set using an average element size of 5 mm, a curvature-based surface refinement with a minimum size factor of 0.1, and a growth rate of 1.2. The number of mesh elements is 491485 for Design 1, 493127 for Design 2, and 491835 for Design 3. The average mesh element size is 5 mm and the use of triangle mesh element on the wall surface and tetrahedral element for the volume mesh provides sufficient mesh generation. The minimum size factor is 0.1, which implies that the smallest mesh elements are 0.5 mm in size, enabling finer resolution in areas requiring higher detail.

2.4 Boundary conditions and CFD simulation setup

The simulation setup employs single-phase incompressible, using air as material for the CFD domain. The analysis is conducted under steady-state conditions and the k-ε turbulence setting is utilized to capture turbulent flows. A convergence tolerance of 0.001 is set. The boundary conditions for the simulation are specified as follows: inlet air velocity is set to 0.9 m/s, the speed at which air enters the CFD domain, and inlet air temperature is set to 308.73 K (35.58°C). For the cell wall, the average heat transfer coefficient is 22.44 W/(m²·K), representing the efficiency of heat transfer between the cell walls and the air, and the wall heat flux is 105.9 W/m², indicating the rate of heat transfer per unit area through the cell walls. For the casing wall, both the average heat transfer coefficient and wall heat flux are set to 0 W/(m²·K), suggesting negligible or no heat transfer across the casing wall, implying insulation.

3.0 RESULTS AND DISCUSSION

3.1 Temperature Distribution

The temperature and velocity distribution for all 3 designs were analyzed at the mid-plane of the cell fluid domain. In general, the air temperature peak of the air is almost similar for all designs, whereby the hotspot locations depend on the ventilation designs. Hot spots are evident around the cells, signifying localized heat generation, with the highest temperatures observed near the cells, particularly in rows 3 and 4 for Design 1 in Figure 2 (a) where airflow appears to be more restricted. The airflow from the inlet significantly influences the temperature distribution, with regions directly in the path of the airflow maintaining cooler temperatures, while areas further from the airflow path exhibit higher temperatures.

The location of the hotspot changes in Design 2 where the center of Row 1 to 4 showed the high temperatures in Figure 2(b). The cell adjacent to the center of the battery pack predicts lower temperatures and becomes hotter at the cells adjacent to the wall of a battery pack. The temperature at the center tends to be high as the inlet air from above is restricted by the top of the cell. As shown in Figure 2 (c) Design 3 showed the position of the inlet and outlet contribute to the temperature distribution. The cells that are near the inlet exhibit lower temperatures compared to cells near to outlet of the casing. The temperature distribution in the Design 3 spot, the greater hot spot at the center of the casing starts from Row 3 to 4 as compared to Design 1 and Design 2.

Design 2 demonstrates the most uniform temperature distribution with minimal hotspots except at the center of the battery pack. Design 3, with different side inlet and outlet positions, shows improved heat dissipation compared to Design 1 but least than the temperature uniformity of Design 2. Design 1 has the most pronounced temperature gradient from the inlet to the outlet, while Design 2 shows the most even temperature distribution. Design 3 falls between the two, with a noticeable gradient but a better distribution than Design 1. Design 2 mitigates hot spots most effectively, with uniform temperatures around the cells. Design 3 shows improved mitigation compared to Design 1, but some central cells still experience higher temperatures. Design 2 with an inlet at the top of the battery casing provides the best heat management, while Design 3 positioned inlet and outlet at the side of the battery casing offers a slight improvement over the linear cooling path of Design 1.

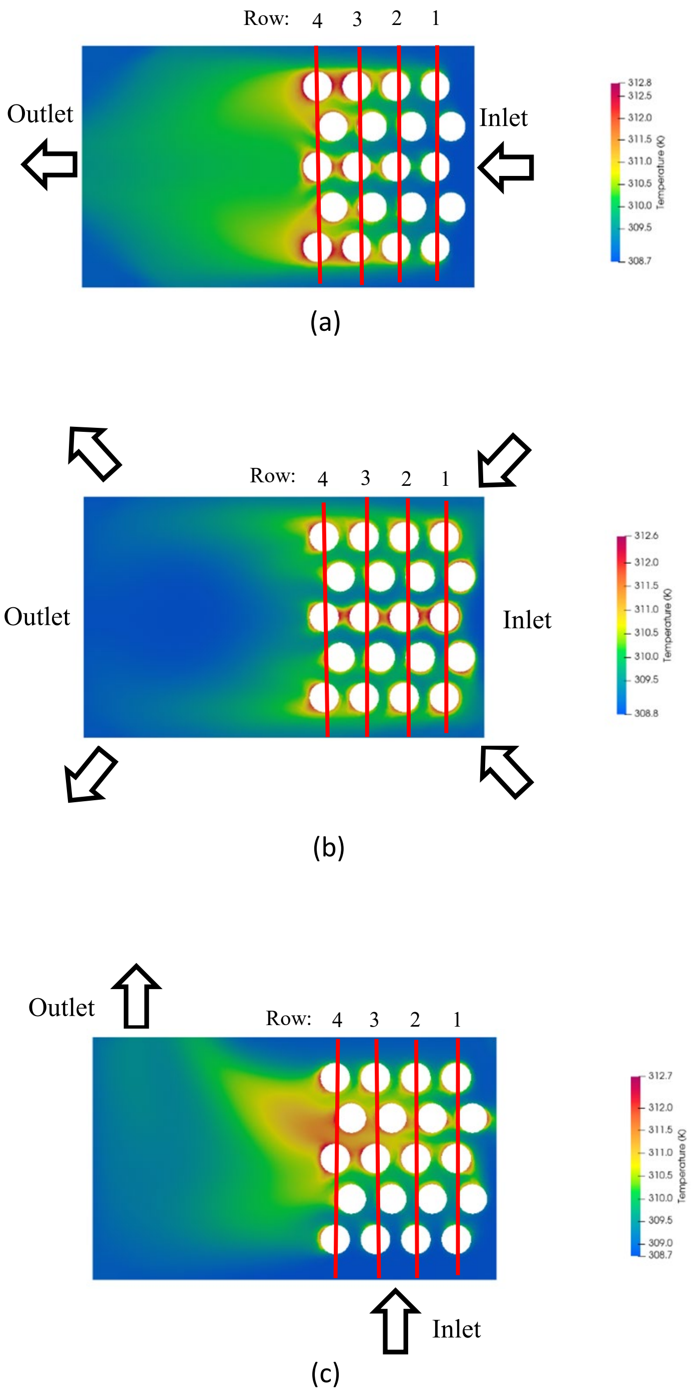

Figure 2: Temperature distribution for a) Design 1, b) Design 2, and c) Design 3 at inlet of 0.9 m/s

3.2 Air velocity distribution

The air velocity distribution for Design 1 demonstrates significant variations in airflow patterns around the cells. The air velocity indicates higher air velocities near the inlet as shown in Figure 3(a) and along the paths directly adjacent to the cells, with velocities reaching up to 2.26 m/s. These regions of high velocity correspond to areas where the airflow is restricted by the battery cells, resulting in increased speed as the air navigates through the narrower gaps. The increase in air velocity corresponds to the enhancement of air convective heat transfer and lower temperatures in these areas. In general, the temperature at the inlet opening, showing cooler regions and the hotspot in the high velocity contribute to lower temperature. This indicates effective convective cooling in these zones, preventing significant heat buildup and mitigating the risk of hot spots. Conversely, lower velocities are observed in the central regions of the battery pack and stagnant air zones were found behind the cells in Row 1 to 4 leading to inefficiency of temperature distribution.

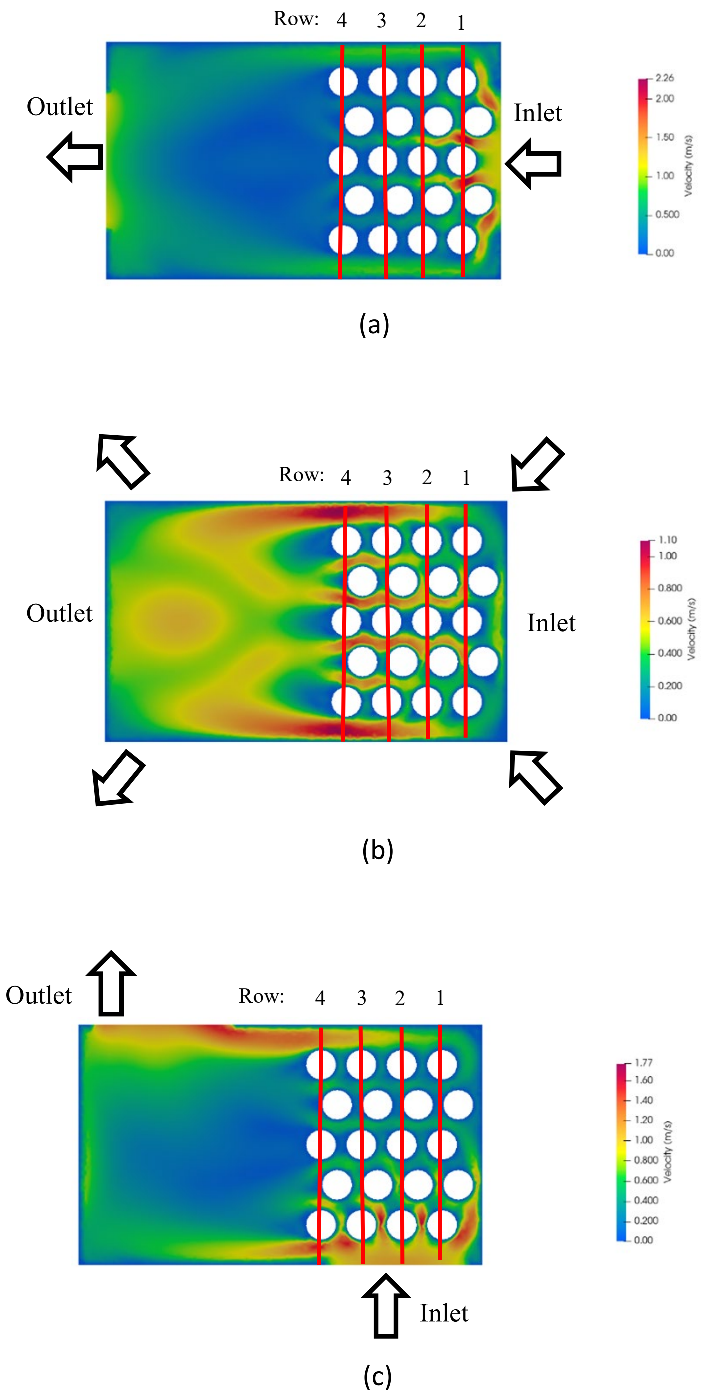

Figure 3: Velocity distribution for a) Design 1, b) Design 2, and c) Design 3 at inlet of 0.9 m/s

The velocity characteristics for Design 2 in Figure 3(b) showed a distinct airflow pattern as the inlet and outlet were positioned at the top and bottom sides of the battery pack. Design 2 indicates that air velocity is higher near the inlet and along the narrow gaps between the cells that suggest, the air velocity can be increased by properly channeling the airflow through an unrestricted path and accelerating within smaller regions. These high-velocity regions with maximum velocities reaching up to 1.1 m/s are characterized by accelerated airflow due to the restricted pathways between the cells, enhancing convective heat transfer in these areas. Lower air velocities as much as 0 m/s are observed in the central regions of the battery pack indicating the stagnant area and contributing to the rise of temperature in the region. The temperature distribution reflects higher temperatures in these low-velocity areas, particularly in the central and outlet regions where the airflow is less intense. The reduced airflow velocity in these areas results in less effective convective cooling, allowing for greater heat accumulation and higher temperatures. The distribution of outlets in Design 2 appears to facilitate a more even spread of airflow across the battery pack, compared to Design 1, potentially contributing to more uniform cooling.

The effect of ventilation design was further studied in Design 3 to determine the airflow patterns influenced by the different sides of the battery pack. Figure 3(c) indicates that the highest air velocities are found near the inlet and in the narrow gaps between the cells, reaching up to 1.7 m/s. In the comparison of Design 1 and 2, Design 3 exhibits different airflow dynamics due to the position of the inlet and outlet. High velocity was found near the inlet and the outlet. The velocity of air exhibits a significant velocity gradient, and that can be traced to the cells behind the first row. This configuration allows for an initial burst of high-velocity air, which gradually slows down as it moves through the pack where the air flows in the restricted spaces. Figure 3(c) indicates that the central regions of the battery pack and areas near the outlet experience significantly lower air velocities, similar to Design 1 but differing from Design 2, which has a more evenly distributed airflow due to its position.

3.3 Effect of ventilation position on the battery cooling

The position of the inlet and outlet in the battery pack ventilation has a battery cooling effect such as the temperature and velocity distribution. The maximum temperature for Design 1, 2, and 3 in the death zone (velocity zero) showed an average of 312.7 K (39.8 ^{0}C) not exceeding the optimal lithium-ion temperature [3]. The position significantly impacts the pattern of airflow and influences the cooling efficiency that also supported by Jianguo, W., et al [27] with the variation of the number of inlets thereby promising a more even temperature and airflow distribution that reduces the number of hotspots. In this study, the region closest to the inlet notified with high velocity and narrow gaps between cells that aligned with the inlet direction will enhance cooling, while regions with low velocity can cause hotspots and increase the potential of thermal failure. Thus, it is important to balance the airflow distribution to achieve even cooling within the cell in the battery pack. This factor is necessary to achieve optimal battery operating conditions by maintaining a stable temperature and preventing the formation of hot spots. The development of hot spots can cause the lithium-ion battery to overheat and degrade over time. Increasing the air velocity directly can enhance convective heat transfer, helping to cool the cells more effectively. However, areas of low velocity may experience insufficient cooling due to obstruction by the adjacent cells, leading to temperature gradients and potential hot spots. Therefore, the design must balance the airflow to ensure uniform cooling across all cells, minimizing thermal stresses and reducing the risk of thermal runaway. These include considering the use of baffles to direct air to areas with insufficient airflow, increasing the number of inlets to allow more air entry points into the battery pack, and adding secondary inlets that focus on areas behind the battery cells experiencing poor airflow.

4.0 CONCLUSION

In conclusion, this study has successfully achieved the objective of investigating the temperature and airflow distribution of lithium-ion batteries for the battery cooling performance that involved 3 ventilation designs. In comparison, Design 2 showed the most efficient cooling strategy, as indicated by the uniform airflow and balanced temperature distribution. The improvement of heat dissipation is notified in Design 3, with the inlet and outlet positioned at the different sides of the battery pack, compared to Design 2. In addition, Design 2 also mitigates hot spots effectively, with more uniform temperatures around cells. Design 3 cooling efficiency falls between the two, with a noticeable gradient but a better distribution than Design 1. The design of the battery pack, specifically the position of the inlet and outlet, significantly impacts airflow and cooling efficiency, resulting in more even temperature distribution and lower peak temperatures. The ventilation design also influences the maximum air velocity within the battery pack. Although high air velocity can enhance the convection of thermal, the distribution of air around the cell must be concentrated to maintain a stable temperature and prevent the formation of hot spots, which can cause lithium-ion batteries to overheat and degrade over time. Integrating baffle and secondary inlet would improve in directing the airflow to the cells and enhance air concentration around cells.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to everyone involved in this project. This research is funded by the Fundamental Research Grant Scheme (600-IRMI/FRGS 5/3(084/2019) from the Ministry of Education, and Universiti Teknologi MARA, Cawangan Pulau Pinang.

REFERENCES

[1] Martin, G., Rentsch, L., Höck, M., and Bertau, M., 2017. Lithium market research – global supply, future demand and price development, *Energy Storage Materials*, 8: 171-179.

[2] Garcia, L. V., Ho, Y. C., Myo Thant, M. M., Han, D. S., and Lim, J. W., 2023. Lithium in a Sustainable Circular Economy: A Comprehensive Review, *In Processes*, 11(2): 1-24.

[3] Rao, Z., and Wang, S., 2011. A review of power battery thermal energy management, *Renewable and Sustainable Energy Reviews*, 15(9): 4554–4571.

[4] Li, Y., Liu, H., and Ye, M., 2022. Optimization of the Heat Dissipation Structure for Lithium-Ion Battery Packs Based on Thermodynamic Analyses, *IEEE Access*, 10: 47250-47265.

[5] Widyantara, R. D., Naufal, M. A., Sambegoro, P. L., Nurprasetio, I. P., Triawan, F., Djamari, D. W., Bayu, A., Nandiyanto, D., Budiman, B. A., and Aziz, M., 2021. Low-Cost Air-Cooling System Optimization on Battery Pack of Electric Vehicle, *Energies*, 14: 7954.

[6] Lin, X., Shao, K., and Wang, C., 2022. Optimization and Numerical Simulation of Novel Air-cooling System for the Thermal Management of Lithium-ion Battery Pack, *International Journal of Electrochemical Science*, 17: 220141.

[7] Shi, Y., Ahmad, S., Liu, H., Lau, K. T., and Zhao, J., 2021. Optimization of air-cooling technology for LiFePO4 battery pack based on deep learning, *Journal of Power Sources*, 497: 229894.

[8] Zhang, S. Bo, Nie, F., Cheng, J. Peng, Yang, H., and Gao, Q., 2024. Optimizing the air flow pattern to improve the performance of the air-cooling lithium-ion battery pack, *Applied Thermal Engineering*, 236: 121486.

[9] Fan, H., Wang, L., Chen, W., Liu, B., and Wang, P., 2023. A J-Type Air-Cooled Battery Thermal Management System Design and Optimization Based on the Electro-Thermal Coupled Model, *Energies*, 16: 5962.

[10] Osmani, K., Alkhedher, M., Ramadan, M., Choi, D. S., Li, L. K. B., Doranehgard, M. H., and Olabi, A. G., 2023. Recent progress in the thermal management of lithium-ion batteries, *Journal of Cleaner Production*, 389: 136024.

[11] Ma, S., Jiang, M., Tao, P., Song, C., Wu, J., Wang, J., Deng, T., and Shang, W., 2018. Temperature effect and thermal impact in lithium-ion batteries: A review, *Progress in Natural Science: Materials International*, 28(6), 653–666.

[12] Lv, S., Wang, X., Lu, W., Zhang, J., and Ni, H., 2022. The influence of temperature on the capacity of lithium ion batteries with different anodes, *Energies*, 15(60): 1-15.

[13] Yang, X. G., Zhang, G., Ge, S., and Wang, C. Y., 2018. Fast charging of lithium-ion batteries at all temperatures. *Proceedings of the National Academy of Sciences,* United States, America, 7266-7271.

[14] Liu, J., Zhang, Y., Bai, J., Zhou, L., and Wang, Z., 2023. Influence of lithium plating on lithium-ion battery aging at high temperature, *Electrochimica Acta*, 454: 142362.

[15] Spitthoff, L., Shearing, P. R., and Burheim, O. S., 2021. Temperature, ageing and thermal management of lithium-ion batteries, *Energies*, 14(5): 1–30.

[16] Park, H., 2013. A design of air flow configuration for cooling lithium ion battery in hybrid electric vehicles, *Journal of Power Sources*, 239: 30–36.

[17] Li, X., Zhao, J., Yuan, J., Duan, J., and Liang, C., 2021. Simulation and analysis of air cooling configurations for a lithium-ion battery pack, *Journal of Energy Storage*, 35: 102270.

[18] Zhang, F., Yi, M., Wang, P., and Liu, C., 2021. Optimization design for improving thermal performance of T-type air-cooled lithium-ion battery pack, *Journal of Energy Storage*, 44: 103464.

[19] G. Y. Cho, J. W. Choi, J. H. P. and S. W. C., 2014. Transient Modeling and Validation of Lithium Ion Battery Pack with Air Cooled Thermal Management System for Electric Vehicles, *International Journal of Automotive Technology*, 15(5): 795–803.

[20] Zhao, J., Lu, S., Fu, Y., Ma, W., Cheng, Y., and Zhang, H., 2021. Experimental study on thermal runaway behaviors of 18650 li-ion battery under enclosed and ventilated conditions, *Fire Safety Journal*, 125: 103417.

[21] Yang, N., Zhang, X., Li, G., and Hua, D., 2015. Assessment of the forced air-cooling performance for cylindrical lithium-ion battery packs: A comparative analysis between aligned and staggered cell arrangements, Applied Thermal Engineering, 80: 55-65.

[22] Zhang, F., Zhu, Y., and Ge, Z., 2022. Thermal Performance of Reverse-Layered Air-Cooled Cylindrical Lithium Battery Pack Integrated with Staggered Battery Arrangement and Spoiler, *Energy Technology*, 10(5): 2101006.

[23] Lu, Z., Yu, X., Wei, L., Qiu, Y., Zhang, L., Meng, X., and Jin, L., 2018. Parametric study of forced air cooling strategy for lithium-ion battery pack with staggered arrangement, *Applied Thermal Engineering*, 136: 28–40.

[24] Choi, J., and Park, H., 2019. Improved cooling performance by staggered cell arrangement of lithium-ion battery pack, *Transactions of the Korean Society of Mechanical Engineers, B*, 43(5): 307-311.

[25] Zhang, S., and Zhang, X., 2021. A multi time-scale framework for state-of-charge and capacity estimation of lithium-ion battery under optimal operating temperature range, *Journal of Energy Storage*, 35: 102325.

[26] Liu, L., Zhang, X., and Lin, X., 2022. Recent Developments of Thermal Management Strategies for Lithium-Ion Batteries: A State-of-The-Art Review, *Energy Technology*, 10(6): 2101135.

[27] Wang, J., Lu, S., Wang, Y., Li, C., and Wang, K., 2020. Effect analysis on thermal behavior enhancement of lithium–ion battery pack with different cooling structures, *Journal of Energy Storage*, 32: 101800.