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The Effect of Battery Settings and Fan Parameters on the Performance of the Lithium-Ion Battery Thermal Management System in a Circular Configuration

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ABSTRAK

Baterai lithium-ion *telah menjadi komponen utama dalam berbagai aplikasi, mulai dari perangkat elektronik portabel hingga kendaraan listrik, karena keunggulannya dalam densitas energi tinggi dan efisiensi pengisian ulang. Namun, tantangan utama yang dihadapi dalam penggunaannya adalah manajemen termal. Penelitian ini bertujuan untuk mengidentifikasi kombinasi parameter yang optimal guna memastikan distribusi suhu yang merata, meminimalkan risiko* overheating*, dan meningkatkan efisiensi termal secara keseluruhan.* Forward-curved *menggunakan jenis penelitian secara kuantitatif. Pengambilan data dilakukan secara eksperimen dengan memvariasikan kecepatan kipas, jumlah bilah, dan posisi baterai (radial atau zigzag) untuk mengamati pengaruhnya terhadap suhu sedangkan distribusi suhu selama proses pengosongan baterai dan analisa data dilakukan melalui statistik deskriptif. Hasil menunjukkan bahwa peningkatan kecepatan kipas secara signifikan menurunkan suhu baterai menjadi sekitar 30-33⁰C dan meningkatkan homogenitas distribusi suhu dengan standar deviasi berkisar 0,5 - 1,21 ⁰C. Sementara itu, variasi jumlah bilah kipas dan posisi baterai menunjukkan pengaruh yang tidak signifikan terhadap penurunan suhu, namun berpengaruh pada keseragaman distribusi suhu dengan standar deviasi terendah suhu pada variasi jumlah 3 bilah berkisar 0,5-0,6⁰C. Sedangkan posisi zigzag memberikan distribusi suhu yang lebih merata dibandingkan posisi radial dengan nilai standar deviasi suhu berkisar 0,51 – 0,97⁰C. Implikasi dari penelitian ini mencakup berbagai aspek teknis dan praktis yang dapat berkontribusi pada pengembangan sistem manajemen termal baterai* lithium-ion*.*

ABSTRACT

Lithium-ion batteries have become a key component in various applications, from portable electronic devices to electric vehicles, due to their high energy density and recharging efficiency advantages. However, the main challenge faced in their use is thermal management. This study aims to identify the optimal combination of parameters to ensure even temperature distribution, minimize the risk of overheating, and improve overall thermal efficiency. The forward-curved uses a quantitative research type. Data was collected experimentally by varying the fan speed, number of blades, and battery position (radial or staggered) to observe their effects on temperature. In contrast, the temperature distribution during the battery discharge process and data analysis were carried out through descriptive statistics. The results showed that increasing the fan speed significantly reduced the battery temperature to around 30-33⁰C and increased the homogeneity of the temperature distribution with a standard deviation ranging from 0.5 - 1.21 ⁰C. Meanwhile, variations in the number of fan blades and battery position showed no significant effect on the decrease in temperature. However, they affected the uniformity of the temperature distribution with the lowest standard deviation of the temperature at the variation of the number of 3 blades ranging from 0.5-0.6⁰C. Meanwhile, the staggered position provides a more even temperature distribution than the radial position, with a standard deviation of temperature ranging from 0.51 to 0.97⁰C. The implications of this study include various technical and practical aspects that can contribute to the development of lithium-ion battery thermal management systems.

1. INTRODUCTION

In electric vehicle systems or renewable energy systems, secondary batteries, which can undergo repeated charging and discharging processes, are an important aspect to consider. Lithium-ion secondary batteries have many advantages, but their performance and safety are sensitive to temperature, either due to temperature changes during charging and discharging or ambient temperature. The performance of these batteries may decrease if the temperature drops below the minimum operational threshold, and heat release, which can cause an explosion, may occur if the temperature significantly exceeds the maximum operational threshold (Lv et al., 2022; H. Wang et al., 2020)(Lv et al., 2020; Y. Wang et al., 2022). These batteries should ideally be operated at temperatures between 15°C and 35°C (Naik & Nandgaonkar,

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2021; Ramadass et al., 2002; Su et al., 2021). Therefore, lithium-ion batteries need careful handling during use, with a good thermal management system that regulates temperature changes during the charge-discharge process, especially during fast charge-discharge cycles. This is in line with the requirements of the ISO 26262 standard for electric vehicles, which stipulates that the probability of Battery Management System (BMS) failure must be measured and kept below a level commensurate with the risk (Marcos et al., 2021; See et al., 2022). Research conducted so far categorizes battery thermal management systems into active systems that use fluid flow, passive systems that do not use fluid flow, and hybrid systems that combine both of them (Patel & Rathod, 2020). In active systems, fluids such as air and liquid are used. Liquid-based active systems offer advantages in terms of specific heat capacity and mass flow rate, allowing faster heat transfer compared to air. However, these systems also have disadvantages, including system complexity due to lithium's reactivity with water if water is used as the fluid, higher installation costs compared to air-based systems, and heavier overall system weight due to the greater density of the fluid and additional components (Shahjalal et al., 2021). Meanwhile, air-based active systems have advantages such as lower production, installation and maintenance costs, and require simpler and fewer components than liquid-based systems systems (W. Li et al., 2023; Shahjalal et al., 2021). However, conventional air-based battery thermal management systems suffer from uneven temperature distribution (Mahek et al., 2023; Saw et al., 2018; Y. Wang et al., 2021).

From previous studies, increasing the homogeneity of battery temperature distribution in active thermal management systems has been achieved by adjusting the distance between battery cells, configuring the air flow between cells, using flow guidance from fans, and increasing the coolant flow rate. In one study, varying the distance between the position of the lithium-ion battery or the ratio between distance and diameter results in a maximum battery temperature reduction of at least 3 K and a temperature difference reduction of more than 60% (Chen et al., 2018; Moosavi et al., 2023; Zhao et al., 2021). Meanwhile, in other research, a simulation was carried out on battery layouts ranging from single row, square, hexagonal, to solid circular layouts, with fans placed at the top, front and sides. It was concluded that a 5x5 grid structure was the best choice in terms of cooling capability and cost, while a hexagonal arrangement with 19 batteries was the best choice for module gap utilization and cooling effectiveness (T. Wang et al., 2014). A similar study varying the configuration and spacing of batteries with natural convection cooling, concluded that dense circular placements performed the worst in cooling, while linear arrangements performed better (Zhang et al., 2020). Other studies have carried out simulations or experimental investigations of battery arrangements, ranging from parallel, staggered, crossed, to tilted configurations (Fan et al., 2019; Kashyap et al., 2024; Yaqien et al., 2024; Ye et al., 2018; X. Yu et al., 2019). In the simulation and experimental studies carried out, the use of plates as air guides in the system achieved the best performance when the air guide plates were placed on top of the battery, thereby reducing the maximum temperature of the battery by 9% (Shahid & Agelin-Chaab, 2018). Most studies use linear or box battery arrangements with airflow coming from one end, resulting in less air volume and uneven temperature distribution at the end farthest from the air inlet. Previous research that used dense circular placement had the weakness of placing the fan at the top or using natural convection, resulting in less than optimal cooling performance in terms of temperature uniformity (T. Wang et al., 2014; Zhang et al., 2020). This temperature non-uniformity can cause uneven resistance, resulting in uneven current in the battery cells, which ultimately accelerates battery degradation over time (S. Li et al., 2023). Therefore, an alternative battery management system is needed that can improve the homogeneity of temperature distribution in air-based thermal management systems without excessive complexity.

Additionally, the use of fans with forward curved blades offers advantages such as higher air flow rates, lower noise, and greater efficiency (Kim & Seo, 2004; Liang & Wada, 2023; J. Yu et al., 2011). In convection studies, the convection heat transfer coefficient is influenced by the Reynolds number which is in turn influenced by the flow rate (Çengel & Ghajar, 2020). Thus, this type of fan has the potential to increase the battery cooling rate. The novelty of this research lies in the analytical approach that integrates battery regulation and fan parameters in the context of a lithium-ion battery thermal management system with a circular configuration, which is still rarely explored. Most previous studies have focused more on linear or planar configurations, without considering the unique heat distribution challenges in circular configurations. Additionally, this research uses a combination of operational parameters such as fan speed, air flow direction, and battery placement to identify optimal thermal solutions. This approach not only provides a new perspective on the design of thermal management systems, but also contributes to the development of experimental and simulation methods that can be applied in the design of modern energy systems. Thus, this research offers unique and practical insights that are relevant for the development of future battery technologies, especially in applications that demand high efficiency and optimal safety. Among the many studies related to battery thermal management systems using forced air convection, circular battery arrangements have not been studied for their performance in terms of temperature and temperature distribution during use, even though this configuration allows more uniform air distribution. Therefore, this study will further investigate the effect of circular battery placement on temperature and distribution during the battery discharge process. To support more uniform cooling, the use of forward curved blade fans is necessary to ensure radial air distribution. Therefore, this research will also explore the influence of various parameters of a fan with forward curved blades on temperature and distribution during the battery discharge process.

2. METHOD

An experimental approach was used to collect data. The experimental design of this research is shown in Table 1. The battery used for data collection was a Camelion brand lithium-ion (Li-Ion) battery type ICR 18650 made from Lithium Cobalt Oxide (LCO) with a capacity of 2200 mAh. . An illustration of the top view of the battery cover and battery placement, both in a radial and staggered arrangement, is shown in Figure 1. From Figure 1, the batteries are arranged in a series of 8 circular cells in both the inner and outer rows. These two rows of circular series are then configured into two radial arrays, the numbering of which is also illustrated in the figure. Thus, this setup results in a total battery voltage of about 4.2V x 8 = 33.6V when fully charged, for a total capacity of about 2.2Ah x 2 = 4.4Ah. The experimental research design is presented in Table 1.

Table 1. Experimental Research Design

Independent Variable		Variable Control	Dependent Variable
Factor	**Level**		
Fan Rotation Speed	• 0 rpm • 3150 rpm	• Total Diameter and Height of Blades • Battery and Blade Material • Discharge Rate	• Final Battery Temperature • Battery Final Temperature Standard Deviation
Number of Fan Blades	• 3 blades • 4 blades • 5 blades		
Circular Battery Arrangement	• Radial • Staggered		

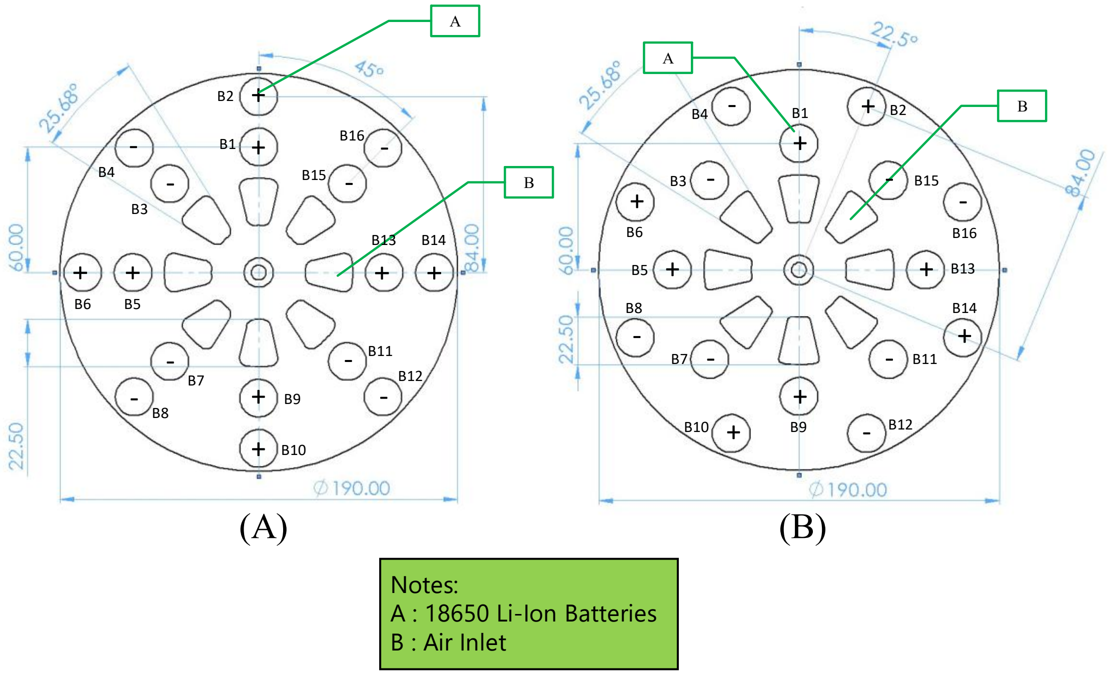


Figure 1. Top Cover Dimensions and Placement of the 18650 Li-Ion Battery from Top View for (a) Radial Arrangement (b) Staggered Arrangement

The thermal management system used during data collection is shown in Figure 2. In this system the top and bottom covers are made of PVC plate material. The DC motor at the top is used to rotate the fan, located in the center of the circular battery configuration. This fan has a total diameter of 100 mm and a height of 56 mm, made through a 3D printing process with PLA material. The fan is positioned in the center of the circular battery array, distributing air radially and tangentially. An illustration of the fan used in the data collection process is shown in Figure 3.

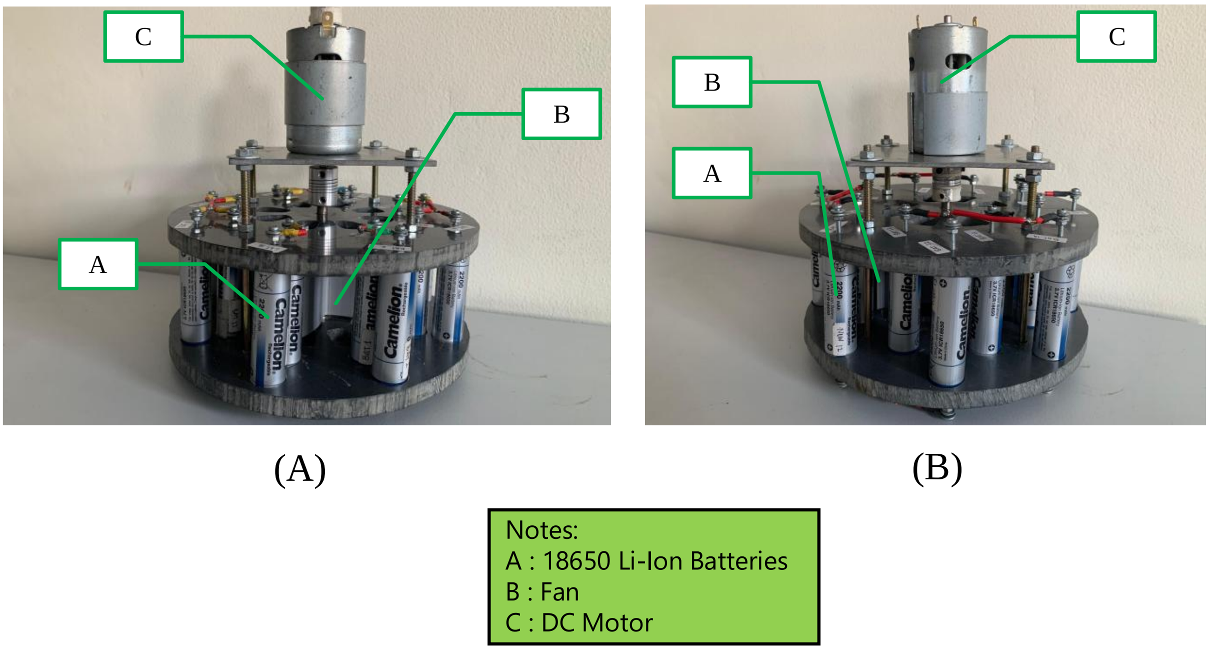


Figure 2. 18650 Li-Ion Battery Thermal Management System for Experiments with (A) Radial Arrangement (B) Staggered Arrangement

Figure 3. Cooling Fan with 3 Blade, 4 Blade, and 5 Blade Variations

The overall experimental setup is shown in Figure 4. During the experiment, the battery was discharged using a TENMA DC 72-13210 Electronic Load with a discharge rate of 1C or 4.4A. This DC Electronic Load can discharge batteries with a maximum power of 300W, voltage 120V and discharge current 0-30A. Battery Management System (BMS) with brand and model JK-BD4A24S-4P, is capable of balancing up to 24 lithium-ion batteries with a balancing current of 0.4A, connected between the DC Electronic Load and the battery for voltage balancing during the discharge process. This is done to prevent the battery cells from experiencing a deep discharge, which could damage the battery or cause a spark. The limitation of this research is that temperature data was not collected during the charging process, and only a discharge rate of 1C was used due to the limitations of the DC Electronic Load and BMS during voltage balancing. The total cut-off voltage at the end of the discharge process set on the DC Electronic Load is 2.83V x 8 = 22.64V. However, because the BMS automatically stops the process when one of the batteries reaches 2.83V, the voltage data at the end of the discharge process for all variations is standardized at around 27.156V, resulting in a different processing time for each variation.

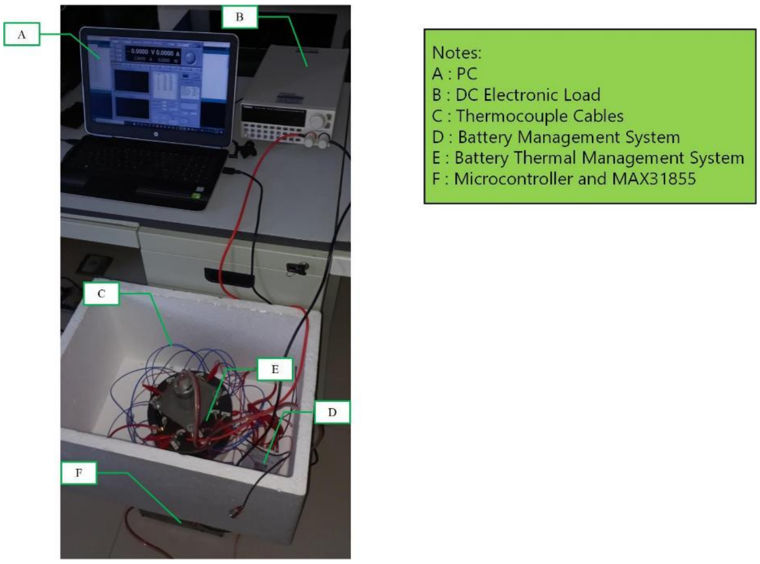


Figure 4. Overall Experimental Setup

During the discharge process, the batteries were placed in a styrofoam box with an initial temperature of around 24-28°C, with the top of the box open for air circulation and were discharged using a TENMA DC Electronic Load 72-13210 with a discharge rate of 1C or 4.4A. The temperature of each battery was measured using a type K thermocouple cable whose end is attached to the middle wall of each battery. This thermocouple cable was connected to a MAX31855 Amplifier module with a data resolution of 0.25°C which is controlled by an Arduino Mega 2560 microcontroller. The DC Electronic Load and microcontroller were connected to a PC for data acquisition. The collected data was then processed using data processing software to obtain the highest final battery temperature (T_{max}) and the lowest final battery temperature (T_{min}) at the end of the release process. The uniformity of temperature distribution among all batteries is represented by the maximum temperature difference (ΔT_{max}) and the population standard deviation of temperature (σ_T), both can be calculated using the following equation, where T_i is the temperature of each of the 16 batteries, and $\bar{T}$ is the average temperature of all batteries.

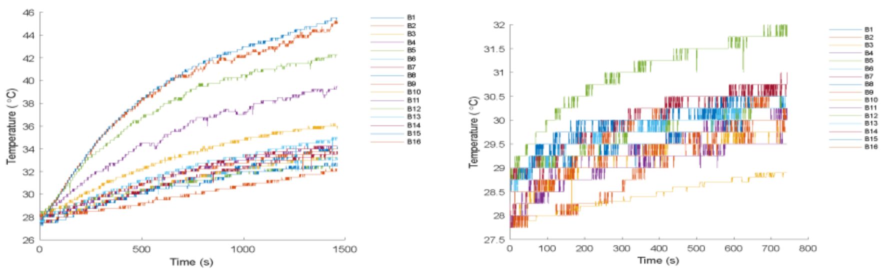
$$\Delta T_{max} = T_{max} - T_{min} \qquad (1)$$

$$\sigma_T = \sqrt{\frac{\sum_{i=1}^{N}(T_i - \bar{T})^2}{N}} \qquad (2)$$

3. RESULT AND DISCUSSION

Result

The results of temperature changes during the discharge process using a discharge rate of 1C for all variations are shown in Figure 5. From the graph it can be seen that the longer the discharge process, the higher the temperature produced by the battery. The graph also shows that the discharge process without using a cooling fan (fan speed 0- rpm), both in the radial and staggered battery arrangement, resulted in a more significant temperature increase in some batteries compared to the fan-cooled process (fan speed 3150 rpm), which caused less uniform temperature among the batteries.



(A) (B)

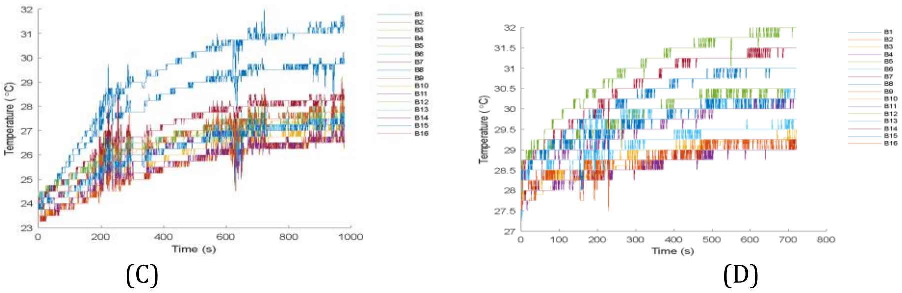


Figure 5. Radial Arrangement Temperature Variation Graph with Mode (A) 0 rpm (B) 3150 rpm, 3 blades (C) 3150 rpm, 4 blades (D) 3150 rpm, 5 blades

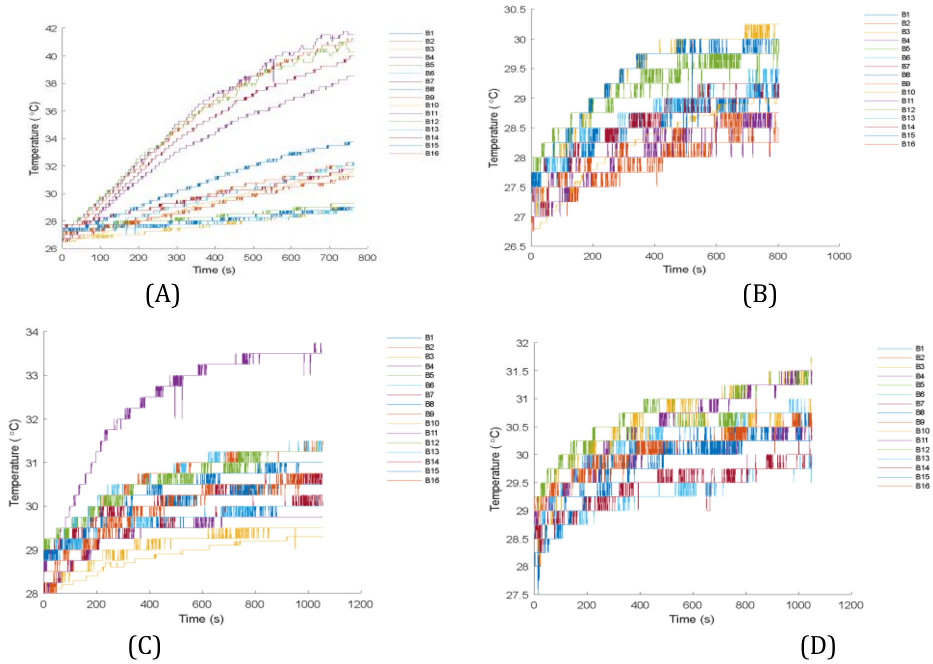


Figure 6. Graph of Staggered Arrangement Temperature Variation with Mode (A) 0 rpm (B) 3150 rpm, 3 blades (C) 3150 rpm, 4 blades (D) 3150 rpm, 5 blades

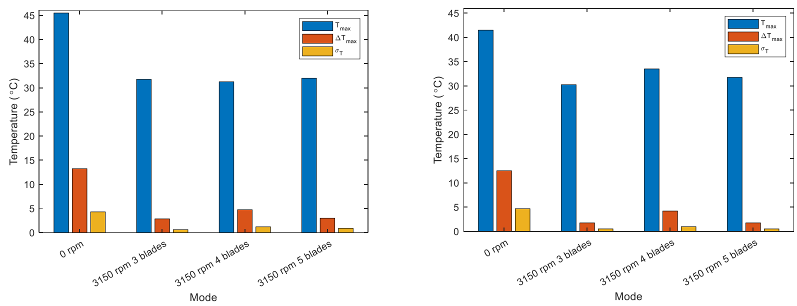
From the graph, recap the smallest initial battery temperature (T_{min_0}), highest initial battery temperature (T_{max_0}), lowest final battery temperature (T_{min}), highest final battery temperature (T_{max}), maximum temperature difference (ΔT_{max}), and the population standard deviation of temperature (σ_T) using equations (1) and (2) can be seen in Table 2.

Table 2. Recapitulation of Battery Temperature at the Beginning and End of the Discharge Process for All Variations

Battery Settings			T_{min_0} (^{0}C)	T_{max_0} (^{0}C)	T_{min} (^{0}C)	T_{max} (^{0}C)	ΔT_{max} (^{0}C)	σ_T (^{0}C)
	0	-	27.5	28.5	32.25	45.5	13.25	4.30
Radial		3	27.8	29	28.9	31.75	2.85	0,62
	3150	4	23.25	24.5	26.5	31.25	4.75	1.21
		5	27.7	28.75	29	32	3	0,90
	0	-	26.5	27.75	29	41.5	12.5	4.68
Staggered		3	26.75	28	28.5	30.25	1.75	0,51
	3150	4	28	29.25	29.3	33.5	4.2	0,97
		5	28.25	29.25	30	31.75	1.75	0,51

Discussion

Comparison Chart T_{max}, ΔT_{max}, And σ_T for each speed mode variation for battery arrangement (a) Radial (b) Staggered is presented in Figure 7.



(A) (B)

Figure 7. Comparison Chart T_{max}, ΔT_{max}, And σ_T for Each Speed Mode Variation for Battery Arrangement (A) Radial (B) Staggered

From these figures, in both radial and staggered battery arrangements, systems with fans operating at 3150 rpm produce lower final maximum temperatures, ranging from approximately 30.25°C to 33.5°C, compared to systems with fan speed 0 rpm, where the temperature ranges from 41.5°C to 45.5°C. This shows that cooling via a fan placed in the middle of the battery arrangement succeeded in reducing the battery temperature during the battery discharge process. In addition, by using this circular battery configuration, cooling performance is improved compared to previous research which was able to reduce battery temperature to 36°C at the same discharge rate of 1C with longitudinal air flow.

This phenomenon occurs because at a fan speed of 0 rpm, heat transfer when discharging the battery only relies on natural convection, with its convective heat transfer coefficient ($h_{natural}$) for cylindrical case is calculated using Equation (3) (Çengel & Ghajar, 2020; Forsberg, 2021). Meanwhile, Ra_L, Gr_D, And T_f which are the Rayleigh number, Grashof number using the battery diameter, and the arithmetic average temperature between the battery surface and the surrounding air, can be calculated using Equations (4)-(6) (Çengel & Ghajar, 2020). Here, L is the height of the battery in meters, D is the diameter of the battery in meters, k is the thermal conductivity of air in W/m·K, Pr is the Prandtl number, T_s is the surface temperature of the battery in Kelvin, T_∞ is the ambient air temperature in Kelvin, v is the kinematic viscosity of air in m^2/s, and g is the acceleration due to gravity in m/s^2. Assuming T_∞ is 27°C or about 300 K, and T_s at the end of the process is approximately 45°C or 318 K, the parameter Pr, k, and v, evaluated at T_f = 309 K in the air property table, are 0.72654, 0.026324 W/m·K, and 0.000016644 m^2/s, respectively. Using Equations (3)-(5) with this data, the natural convection coefficient is calculated to be $h_{natural}$ = 6.24 W/m^2.

$$h_{natural}\left(\frac{W}{m^2}\right) = \left(1{,}3\left(\frac{\left(\frac{L}{D}\right)}{Gr_D}\right)^{\frac{1}{4}} + 1\right)\left(\frac{k}{L}\right)\left(0{,}825 + \frac{0{,}387 Ra_L^{\frac{1}{6}}}{\left(1+\left(\frac{0{,}492}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right)^2 \quad (3)$$

$$Ra_L = \frac{g\left(\frac{1}{T_f}\right)(T_s - T_\infty)L^3}{v^2} Pr \quad (4)$$

$$Gr_D = \frac{g\left(\frac{1}{T_f}\right)(T_s - T_\infty)D^3}{v^2} \quad (5)$$

$$T_f(K) = \frac{1}{\frac{T_s + T_\infty}{2}} \quad (6)$$

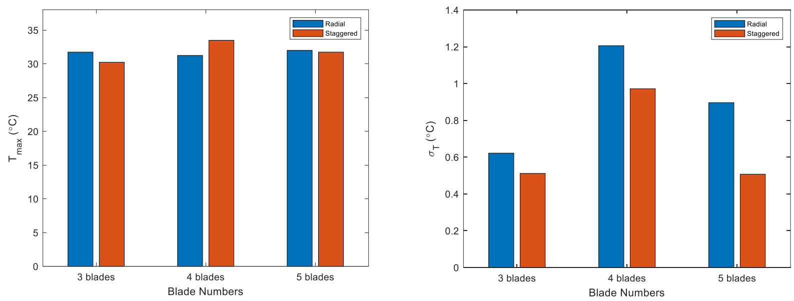
In contrast, a system with a fan speed of 3150 rpm operates with forced convection. Convection heat transfer coefficient for forced convection (h_{forced}) for the case of external flow on a cylindrical surface can be calculated using Equation (7) where Re is the Reynolds number which can be calculated using Equation (8) (Çengel & Ghajar, 2020). Based on measurements made with an anemometer, the fan at this speed produces an air flow velocity (ϑ) about 1.52 m/s. Assuming T_∞ is 27°C or 300 K, and T_s at the end of the process is about 33°C or 306 K, the parameter Pr, k, and v, evaluated at T_f = 303 K in the air property table, respectively are 0.7282, 0.02588 W/m·K, and 0.00001608 m^2/s. Using Equations (7)-(8) with this data, the forced convection coefficient is calculated to be h_{forced} = 30.48 W/m^2.

$$h_{forced}\left(\frac{W}{m^2}\right) = \left(\frac{k}{D}\right)\left(0.3 + \frac{0.62Re^{0.5}Pr^{\frac{1}{3}}}{\left[1+\left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}\left[1+\left(\frac{Re}{282000}\right)^{\frac{5}{8}}\right]^{\frac{4}{5}}\right) \tag{7}$$

Where

$$Re = \frac{\vartheta D}{v} \tag{8}$$

From these calculations, it can be seen that the estimated value of h_{forced} during the discharge process with the fan operating at 3150 rpm is much higher than $h_{natural}$ with the fan at 0 rpm. This explains why the battery temperature during discharge is much lower at 3150 rpm, because the convection process is more effective due to the air flow speed or convection mode (Kirad & Chaudhari, 2021; Morali, 2024). Figure 7 also provides information that, with the fan operating at 3150 rpm, both ΔT_{max} And σ_T decreased significantly, with values ranging from 1.75°C to 4.75°C and from 0.5°C to 1.21°C, respectively. This shows that increasing the fan speed will increase the uniformity of temperature distribution across the battery. These results are better than those reported in studies where cooling simulations were carried out by placing cooling plates around the battery to circulate air or varying gap distance scenarios and ΔT_{max} from this work is around 5 – 12.9°C with the same charge/discharge rate (Ardhyanti et al., 2023; Zhao et al., 2021). Influence of the number of blades and battery arrangement T_{max} and the uniformity of temperature distribution is shown in Figure 8. Figure 8(A) shows that the number of blades, both in radial and staggered battery arrangements, does not have a significant effect on the maximum temperature reduction of the battery which ranges from 32°C to 33°C. A similar phenomenon occurs in variations in battery arrangement for the same number of blades, where the arrangement does not significantly affect the decrease in maximum battery temperature. Comparison Graph (A) T_{max}, and (B) σ_T For each variation in the number of knives for the radial and staggered battery arrangement, it is presented in Figure 8.



(A) (B)

Figure 8. Comparison Graph (A) T_{max}, and (B) σ_T for Each Variation of Number of Blades for Radial and Staggered Battery Arrangements

However, the number of blades does influence the uniformity of temperature distribution, although not in a linear relationship. Figure 8(B) shows that, for both radial and staggered battery setups, the smallest standard deviation in final temperature occurs with 3 bars, ranging from 0.5°C to 0.6°C, indicating the best temperature uniformity. With fewer blades, the airflow area increases, creating more favorable airflow conditions, as reported by one study, leading to more uniform convection (Yin et al., 2024). Additionally, placing the batteries in a staggered arrangement will result in a more even temperature distribution. Figure 8(B) shows that, for all blade variations (3, 4, and 5), the standard deviation of the final battery temperature for the staggered arrangement is lower, ranging from 0.5°C to 0.9°C, compared with radial arrangement, which ranges from 0.6°C to 1.2°C. This phenomenon is most likely due to the fact that the outer rows of batteries are not as close to the inner circle in a staggered arrangement as they are in a radial arrangement, so the heat generated by each row does not significantly affect the other rows. Additionally, the outermost rows in a staggered arrangement receive airflow directly from the fan, compared to the outermost rows in a radial arrangement, which results in more uniform convection through the air. This can be seen in Figure 9, where the average temperature difference between the inner circle and outer circle in the staggered arrangement is not significantly different, regardless of the number of blades (3, 4, or 5), compared to the radial arrangement. These results are also consistent with findings in previous studies where staggered settings provide better cooling distribution than in-line settings because these settings dissipate heat better, reduce cell-to-cell temperature variations, and increase the heat transfer coefficient although this study did not take advantage of this circular arrangement (Kashyap et al., 2024). This uniformity result is better than previous research where the standard deviation of battery temperature was around 6°C using an in-line configuration (Fan et al., 2019). In this research, one of the causes of uneven temperature distribution could be that the battery row farthest from the fan receives the smallest air flow from the fan. Meanwhile, this circular configuration has the advantage of distributing air flow to the battery more evenly. The application of this method can be applied to automotive or renewable energy applications where the use of lithium ion batteries is highly recommended at operating temperatures. However, the disadvantages of the current system are the more complicated configuration of cables or connecting rods and the larger space due to the fan size, so improvements in these issues are urgently needed to apply this configuration in real automotive and renewable energy cases in the future research. Another consideration for future research is further investigation of fan blades to improve battery cooling performance. Furthermore, to better understand the phenomena that occurred in this experiment, research related to Computational Fluid Dynamics (CFD) is highly recommended for future research.

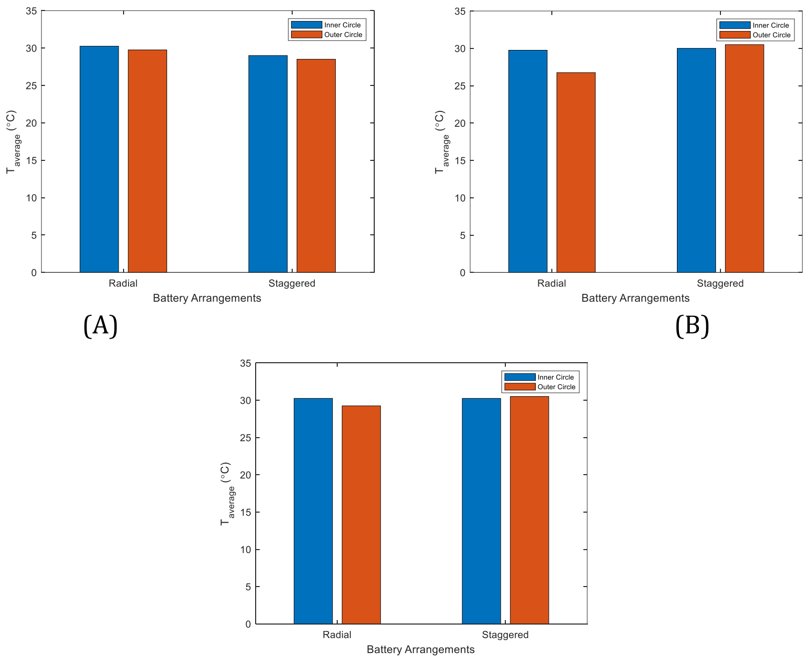


Figure 9. Average Temperature Comparison Chart $T_{rate\ by\ rate}$ Between Inner and Outer Battery Circles for Radial and Staggered Battery Arrangements with Varying Blade Numbers (A) 3 (B) 4 (C) 5

The implications of this research provide a significant contribution to the development of lithium-ion battery thermal management systems, especially in circular configurations. From a technical perspective, the research results can be used to design more efficient cooling systems, with fan parameters and battery settings optimized to distribute heat evenly and prevent overheating. This not only improves battery performance and lifespan, but also reduces the risk of system failure due to thermal runaway. From an industrial perspective, these findings can be applied to battery design for electric vehicles, energy storage systems, and portable devices, thereby improving product safety, reliability, and efficiency. Another implication is the potential for reduced energy consumption in cooling systems, supporting environmental sustainability. Overall, this research could form the basis for the development of more advanced thermal technologies and support wider adoption of lithium-ion battery technology in various sectors. The limitation of this study lies in its limited focus on the analysis of fan parameters and battery arrangement in a circular configuration, so it does not include other external factors, such as variations in the surrounding environment (e.g., temperature and humidity) or the influence of dynamic battery charging and discharging cycles. Additionally, this research uses certain experimental or simulation approaches that may not fully represent real operational conditions on a large scale. Therefore, for further development, it is recommended that future research consider more diverse environmental conditions as well as integrate other operational factors, such as alternative refrigerant design or artificial intelligence-based smart control systems. Additional research could also focus on validating the results through large-scale testing in various practical applications, such as electric vehicles or energy storage systems, to ensure broader and more relevant applicability of the results of this research.

4. CONCLUSION

Based on the experimental research carried out, it can be concluded that the use of a circular battery arrangement combined with a forward curved fan placed in the middle of the circular row of 18650 batteries produces a significant effect on both reducing battery temperature and decreasing battery temperature. its distribution. By increasing the fan speed, the maximum battery temperature can be reduced significantly when compared to a system with zero fan speed. On the other hand, the number of fan blades and battery position do not have a significant effect on reducing battery temperature. However, the number of blades has a greater impact on the temperature distribution, although this relationship is not linear. The lowest standard deviation in battery temperature was observed with a 3-blade fan, in both staggered and radial battery configurations. Additionally, the staggered arrangement facilitates a more uniform temperature distribution compared to the radial arrangement, as indicated by the lower final standard deviation of the battery temperature.

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