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Original Article

Thermal Analysis of Lithium-Ion Battery for Radial and Axial Heat Dissipation

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Abstract *- Electric cars cannot function without Li-ion batteries. However, concerns over battery longevity have slowed the spread of electric automobiles. The temperature inside the battery pack is critical to maintaining a healthy battery for as long as possible. A cooling system is helpful because it can keep batteries from dying too quickly. Using finite element analysis, the thermal behaviour of a cylindrical battery module has been examined with axial-radial thermal routes. The rate of heat production and thermal transport parameters of Li-ion cells has been evaluated. One surface of a cylindrical Li-ion cell is heated radially or axially while the remaining surfaces remain at a constant ambient temperature.*

Keywords *- Li-Ion battery, BTMS, Axial heat transfer, Radial heat transfer, Thermal management.*

1. Introduction

Lithium-Ion batteries are widely considered the alternative power supply for automobiles. They have seen significant applications in electric vehicles due to their high energy storage density, extended cycle life, and low self-discharge rate. Unresolved issues in current Lithium-Ion batteries include the need for ever-increasing energy density, thermal safety, and thermal control under high-speed charging and discharging. Effective thermal management solutions must be developed so that battery systems can operate at high discharge rates while maintaining low battery temperatures. This helps keep the battery from overheating and shorting out [1-3].

Most BTMS fall into one of four categories: air cooling, liquid cooling, Phase Change Materials (PCMs) cooling, and hybrid cooling, which combines two or more of these cooling methods. Air cooling has been frequently employed for portable battery packs of all sizes due to its low cost and ease of implementation. However, because of its lower specific heat capacity and thermal conductivity, air cooling presents challenges associated with temperature non-uniformity.

Phase Change Material (PCM) can enhance thermal performance in battery thermal management systems by maintaining the battery module at an optimum temperature for a prolonged time, even when subjected to fast charging and discharging rates. However, the cooling may fail if the PCM melts after being put through several use cycles.

Therefore, advancing battery thermal management systems utilizing phase change materials and other cooling strategies is essential for the thermal management of battery modules under continuous operation. However, the drop in energy density brought on by adding PCM may limit its practical application. However, liquid cooling has become the thermal management technology for most modern electric vehicles because of its higher heat transfer capability. Most previous studies have focused on the effectiveness of cooling battery cells with surrounding liquid [4-6].

A new thermal management system might be created using the combination of a lateral heat dissipation structure and a bottom excellent plate to prevent liquid from escaping from the battery module. Numerical simulation methods are commonly used to determine the best settings for the structural parameters. The analytical solution for a liquid-cooled battery module still faces obstacles, however. These may result from a lack of theoretical work on the battery with internal heat generation or the complexity of the battery system itself, such as a cooling arrangement with both a lateral and bottom heat dissipation thermal channel. Thermal analysis utilizing direct analytical expressions is helpful for quickly evaluating the battery's thermal performance; therefore, more study is encouraged in this direction with the goal of design optimization [5, 6, 21, 22].

This study investigates using coaxial tubes, thermal diffusion plates, and thermal columns as part of a cooperative cooling thermal structure for an anisotropic battery module. An axial-radial cooperative cooling thermal architecture for a liquid-cooled battery module is developed after a numerical simulation to discover which structural characteristics impact thermal performance most.

By building a heat-resistance network, the optimum structural parameters can be discovered analytically, eliminating the need for the time-consuming numerical technique. The current analytical method can be used for rapid thermal design research, and it helps enhance anisotropic battery design.

This work examines the radial and axial heat dissipation of a Li-ion NMC battery using experimental and FEA techniques. Please find out how well they function thermally. Examine the difference between radial and axial heat transfer, and verify the FEA results using an experimental setup. Create plans and suggestions to enhance Li-ion battery thermal management's efficiency, durability, and security. This study aims to conduct a complete radial and axial heat dissipation thermal investigation of Li-ion NMC batteries. This research aims to learn more about the thermal characteristics of a Li-ion NMC battery in different usage scenarios to implement better thermal management.

The scope of the work is to analyze the Li-Ion battery and investigate temperature distribution and heat dissipation mechanisms in the Axial and Radial direction of the cell. Compare the Axial and Radial heat dissipation rates.

The methodology of the work is as follows:

1. A 3D model of the Li-Ion battery is prepared using Solid Works software, where the battery's geometry and dimensions are fixed. The specific arrangement and structure of the battery cells are selected to represent the radial and axial heat dissipation paths accurately.
2. Finite Element Analysis (FEA) is used to simulate the thermal behaviour of the Li-Ion battery. A battery model is implemented, and heat generation analysis, thermal conduction equations, and boundary conditions are used in the ANSYS software. Simulation is performed to obtain the temperature distribution and heat dissipation.
3. Experimentation has been conducted, and simulation results are validated by comparing them with experimental data.

2. Related Work

The present car industry offers a wide variety of hybrid electric vehicles, as well as pure electric vehicles, with varying degrees of hybridization. The size, kind, and number of battery cells installed in EVs vary with the mixing level. As an energy source, battery cells have more stringent requirements for the working environment than conventional fuel. They are highly temperature-dependent. A Battery Thermal Management System (BTMS) is typically incorporated with battery cells to maintain an appropriate thermal working environment. Therefore, it is crucial to understand the needs of a working battery and the types of management systems that may adequately and efficiently supply those needs. With this foundation, an electric vehicle's battery pack may function at peak efficiency and last as long as possible. In addition, the battery capacity limits the electric vehicle's range. Savings can be gained by in-depth research into BTMS's electric energy consumption. By lowering BTMS energy usage, this study will improve battery performance, allowing EVs to go farther on a single charge.

Numerous studies have been conducted on BTMS technology, and freely available design and simulation approaches exist. However, the technologies employed by each BTMS cause them to diverge significantly from one another. Therefore, a single simulation model cannot adequately predict the overall system performance. Although the data is not separated by BTMS type, various simulation models and approaches can be applied to these simulations. Because of this lack of structure, developing a BTMS is more challenging than it needs to be.

Additionally, the quality of these systems/models varies, making it more difficult to compare the outcomes of various models. This article includes a sample simulation run on a standard 2-wheeler battery to bring order to the abundance of online simulation research. The study also analyses and compares the various models to craft the best possible answer.

Tedjani Mesbahi et al. [1] offered several heat generation mechanisms and transmission paths as part of their thermal model for Li-Ion batteries. It explains why precise thermal modelling is essential for improving battery efficiency and longevity.

Various thermal control strategies for Li-Ion batteries were summarized by Jianbo Li et al. [2]. It explores and rates the efficiency of active, passive, and phase change materials for controlling battery temperature. Li-Ion batteries generate heat by various methods, including joule heating, entropic heating, and electrochemical reactions, all discussed by Guangming Liu et al. [4]. It explores the causes of excess heat and offers advice on dealing with the problem through thermal management.

The foundations of heat transmission in Li-Ion batteries, including conduction, convection, and radiation, were discussed by Rajib Mahamud, and Chanwoo Park [5]. Several thermal management methods are discussed, and the difficulties of efficient heat dissipation are emphasized. Heat transfer enhancement strategies for Li-Ion batteries were the topic of study by Vivek Vishwakarma et al. [7]. Improvements in thermal performance and protection against thermal runaway are discussed, along with the role of new materials, micro/nanostructured surfaces, and optimization methodologies.

Thermal study of Li-Ion batteries for usage in electric vehicles was the main topic of Zhang et al. [8]. The paper highlights the significance of thermal management in Li-Ion batteries and provides a thorough thermal analysis method. This research delves into the origins of the battery's internal heat, how that heat is transferred, and how operating conditions affect the battery's overall temperature profile. It sheds light on enhancing the thermal design for a more robust and secure battery.

Zhang et al. surveyed the state of the art in thermal analysis and thermal management for Li-Ion batteries. It analyses several thermal management systems and discusses the difficulties caused by heat generation and dissipation in Li-Ion batteries. The paper discusses sophisticated cooling strategies, thermal characterization methodologies, and modelling. It is an excellent reference for learning about the cutting-edge thermal management of Li-Ion batteries [9].

An extensive investigation of thermal difficulties in Li-Ion batteries, including heat generation, heat transmission, and thermal management solutions, was presented by Sun et al. [10]. Thermal analysis methods, including numerical simulations and experimental approaches, are discussed for studying battery temperature distribution. Active cooling, passive cooling, and thermal interface materials are all discussed in the study as thermal management methods. It offers helpful information for developing efficient Li-Ion battery temperature management systems [11]. Active (air-cooled) and passive (phase change material) thermal management methods were explored by Rami Sabbah et al. The active cooling system uses air as a coolant to dissipate heat from the battery pack. However, Phase Change Materials (PCMs), which absorb and release heat during phase transitions, are used in the passive technique to achieve the same effect [12].

Hybrid Electric Vehicles (HEVs) and Electric Cars (ECs) can benefit from insights into battery heat management provided by Hafiz Muhammad Ali [13]. The paper probably discusses a wide range of topics associated with battery thermal management, such as the many technologies and methods used to control battery temperature. The 'Inverse Method' introduced by Hanumanth Reddy Palle [14] is a novel strategy for estimating heat generation rates in Lithium-Ion cells. Accurately forecasting and monitoring the temperature behaviour of Lithium-Ion batteries is critical to ensuring their safe and effective operation, and this study set out to do just that.

Current research status and critical technologies related to battery heat management and safety enhancement were the topics of a recent paper [15] by Yan Wang et al. The purpose of this study is to present a synopsis of the literature on battery temperature management and the methods used to improve battery safety. It discusses a wide range of topics, including thermal modelling and simulation, cooling methods, and cutting-edge materials for heat transfer. The authors investigate both passive and active cooling techniques and compare and contrast them.

Prominent in the field of battery temperature management systems for electric and hybrid electric cars is Ahmad Pesaran [16]. He is connected with the National Renewable Energy Laboratory (NREL), a pioneering centre for renewable energy study. Pesaran's work focuses on battery thermal management, including challenges like temperature regulation, heat production and distribution within the battery pack, and thermal stability overcharging and discharging cycles. These aspects significantly affect the effectiveness, longevity, and dependability of batteries used in electric vehicles. The history and significant milestones of lithium-battery development were briefly summarised in Mogalahalli Reddy et al. [17].

In 2017, Zhenpo Wang et al. [18] used finite element analysis to create and simulate a thermal model for cylindrical Lithium-Ion (Li-ion) batteries. Temperature fluctuations significantly affect the performance and longevity of Li-ion batteries and can even cause thermal runaway events; therefore, proper thermal management is essential for their safe and effective functioning. Xianxia Yuan et al. (2011) [19] thoroughly reviewed Lithium-Ion batteries, emphasizing the cutting-edge materials and techniques that went into their creation. This comprehensive guide examines every facet of Lithium-Ion batteries, from their chemistry and electrochemistry to their performance and safety. Future possibilities and new trends for developing Lithium-Ion battery technology are also discussed.

Hyun Woo You et al. Lithium-Ion battery behaviour equivalent circuit analysis was the primary focus. Electrical simplifications called equivalent circuit models can capture complicated systems' essential features and dynamics. Battery research and engineering rely heavily on these models to better comprehend battery operation, create more effective battery management systems, and foretell battery behaviour in various scenarios [20].

3. Experimentation on Li-Ion Battery for Thermal Analysis

3.1. Heat Generation in Li-Ion Battery

Understanding the internal makeup of a battery is a prerequisite for deducing its heat-generation principle. The following components contribute to the heat: The heat generated by the current due to polarisation resistance, the heat generated by the chemical reaction and the ohmic resistance, and the heat generated by the side reaction material. As the number of battery cycles rises, the side reactions generated by lithium deposition in the battery and the disintegration of SEI film can be disregarded compared to the total battery heat. Zhang et al. [9] devised the following formula for the calculation. The three primary types of heat transport in a battery pack were analyzed by Guangming Liu et al. [4]: conduction, convection, and radiation.

Polarization heat of Q_p is the battery about polarization resistance, J.

$$Q_p=I^2R_p$$

Where I is current, A and R_p are resistance of polarization, Ω.

Joule heat of Q_e is the heat generated by the resistance inside the battery during the workingprocess, J.

$$Q_e=I^2R_e$$

Where, R_e is the electronic flow resistance, Ω.

The calorific value of Lithium-Ion batteries is mainly composed of polarization and jouleheat, J.

$$Q_s=I^2R_t = Q_p+Q_eR_t = R_p+R_e$$

$$Q_s=I^2R_t/S$$

R_t is the internal resistance of the battery, Ω, Q_s is the battery heating power per unit area, J and S is the Area of heating surface on a single battery, m^2.

3.2. Experimental Analysis

A Li-ion 26650 battery, also known as Lithium Nickel Manganese Cobalt Oxide, i.e., NMC, is used, arranged in 3×3 format and fixed in the frame. Those battery cells are connected in series by copper wiring arrangement. The thermocouple is an instrument used for measurements of temperature variations. All the setup is kept in one box. An experiment was carried out to take temperature variation during the charging and discharging of the battery. CN-8760, a silicon-based material, improves heat conductivity in axial and radial directions. Grey elastomer with moderate thermal conductivity, two-component (1:1), room temperature and heat curable for production versatility. A liquid must be combined with another liquid at a 1:1 ratio. Such a liquid, once mixed, will solidify after 30 minutes. For accurate heat transfer, the same method must be employed in both the axial and radial directions. A few features of it are listed below.

- Low viscosity, i.e., 2.8 Pa-Sec after mixing
- Good thermal conductivity, i.e., 0.66 W/m^2K
- Room temperature curing
- Good flowability for fast processing and short cycle times
- Aids heat dissipation

Experimentation has been carried out and measured temperature rise during charging and discharging of the battery as shown in Figure 1 and measured temperature rise during charging and discharging of battery. Temperature rise is observed in radial and axial cases, and the readings are storedfor future reference. The time interval used for reading was 10 minutes. First readings while discharging were taken for 30 minutes and then rest for the battery to come to the surrounding temperature. After achieving the equilibrium, again reading was taken while charging the battery. Temperature readings for radial heat dissipation during discharging and charging is available in Table 1 and Table 2 respectively.

Fig. 1 Experimental setup for temperature measurement in Li-ion battery

Table 1. Temperature readings for radial heat dissipation during discharging

Trials	**Temperature (^{o}C)**
Trial 1	31.8
Trial 2	38.3
Trial 3	44.8

Table 2. Temperature readings of radial heat dissipation during charging

Trials	**Temperature (^{o}C)**
Trial 1	31.5
Trial 2	39
Trial 3	45.6

Table 3. Axial heat dissipation during discharging

Trials	Temperature(^{o}C)
Trial1	31.5
Trial 2	32.8
Trial 3	34.6

Table 4. Axial heat dissipation during charging

Trials	Temperature(^{o}C)
Trial 1	31.3
Trial 2	33.3
Trial 3	35.6

The experimentation was also carried out for the axial heat transfer case, and readings were noted for reference. Thermal padding is used in the axial direction to enhance the heat transfer in an axial direction. The time interval used for reading was 10 minutes.

First readings while discharging were taken for 30 minutes and then rest for the battery to come to the surrounding temperature. After achieving the equilibrium, again reading was taken while charging the battery. Axial heat dissipation during discharging and charging is given in Table 3 and Table 4 respectively.

4. Thermal Analysis of Li-Ion Battery by using Finite Element Method

Various thermal models used for battery cells were found in the literature. The different models have a different impact on the accuracy of the heat transfer in the cell (Vivek Vishwakarma et al.) [7]. The thermal model is applied to investigate the temperature profile of the battery cell during the battery's operation. The study by Ahemd Pesaran [16] presents and summarized standard models. These models are the following:

- Lumped thermal model
- Partial Differential Equations (PDEs) models
- Finite element analysis battery model

4.1. Lumped Capacitance Thermal Model

All components inside the core, including the anode, cathode, active material, etc., are assumed to be a single homogenous material with averaged properties (Ahemd Pesaran)[16], and the battery core and battery case are treated as two separate isothermal nodes in the model. In addition to the lumped thermal model, Vivek Vishwakarma et al. [7] suggest a lumped electric equivalent model.

The research focuses on simulating the thermal behaviour of a large prismatic Li-ion battery and validating that behaviour experimentally. We construct a one-dimensional lumped thermal model. The cell's specific heat capacity, thermal resistors, and heat output are all needed for the model. The simulation demonstrates the model's viability in offline applications like a pack thermal design tool or a building management system. Such a model can be created with the help of the simulation programme MATLAB/ Simulink.

4.2. Partial Differential Equations Models

Nonlinear partial differential equations are used in the models so that the dynamics of the systems can be represented appropriately. A set of coupled nonlinear partial differential equations is a mathematical representation of the models' complicated structure. The PDE model is precise, but Nguyen Huy Hoang et al. [21] research shows that it is also mathematically tricky and takes a long time to simulate.

4.3. Finite Element Analysis Battery Thermal Model

The model provides a three-dimensional account of the heat transmission in a battery. This is demonstrated in the research by Zhenpo Wang et al. who created a finite element analysis battery thermal model of a cylindrical Li-ion battery. [18] The model is accurate and practical for investigating cellular and environmental thermal dynamics. However, a large amount of data (which can be derived from either theoretical analysis or experimental results) is needed for the model, and without high-powered computers, the simulation time may be prohibitive. ANSYS can be used to create the model.

4.4. Model Making

We intend to analyze the heat transfer along the axial and radial direction of the battery cell. We have assumed steady-state thermal conductivity, and the material is isotropic. Two different models are prepared using solid works software as shown in Figure 2 and Figure 3, one is for axial heat transfer, and the other is used to analyze radial heat transfer, which will be used as geometry for actual analysis using Ansys 18.0 software. A model of Cell Container is shown in Figure 4.

4.5. Material Data

The thermal conductivity of Li-Ion NMC cells is relatively low. It means they are not very efficient at conducting heat, which can result in heat buildup within the cell during operation. During charging and discharging, Li-Ion NMC cells generate heat due to various electrochemical reactions within the cell. The heat generation is typically higher at higher charge/discharge rates. If the temperature of a Li-Ion NMC cell rises too high, it can lead to a thermal runaway situation.

Thermal runaway refers to an uncontrollable temperature increase, which can release gases, venting, or even a cell rupture. The thermal properties of the Li-Ion NMC 26650 cell are listed in Table 5, used during experimentation.

Table 5. Material data: thermal properties of Li-Ion NMC 26650 cell

Name	Material	Thermal Conductivity (W/mK)
Cell	Li-Ion (NMC)	X, Y- 2.1, Z-2.1
Cell Holders	ABS	0.2
Busbars	Nickel	65
Heat Dissipation Material	Silicon based PadCN-8760	0.7
Casing	CR Steel	45

Fig. 2 Model for radial heat dissipation

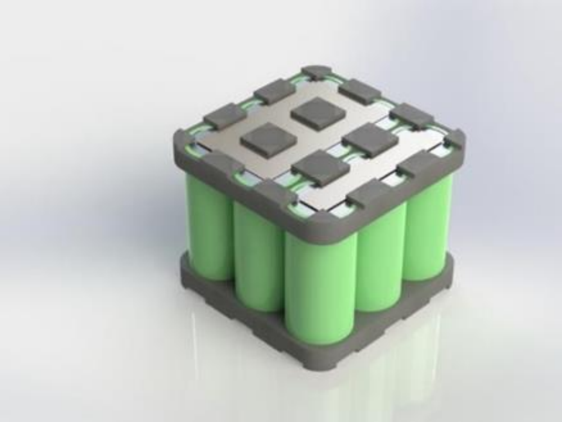


Fig. 3 Model for axial heat dissipation

Fig. 4 Model of cell container

Input Data

Steady-state thermal condition is used for the analysis of the heat dissipation.

Heat generation = I^2R = 0.344 W/Cell
Volume of cell = $\pi/4\times(0.026^2)\times(0.065)$
= 0.0000344 W/mm^3
Heat generation per mm^3 = 0.344/0.0000344
= 10,000 W/mm^3
Heat generation from cells = I^2R = 10,000 W/mm^3
Ambient temperature = 30°C

Convection heat transfer from the outer surface of the casing to the surrounding, i.e. natural convection = 5 W/mm^2

Resistance = 20 μΩ Per cell
Load = 4.15 A

The required results from FEA are temperature and total heat flow. The following conditions are applied in Ansys software 18, and results were obtained.

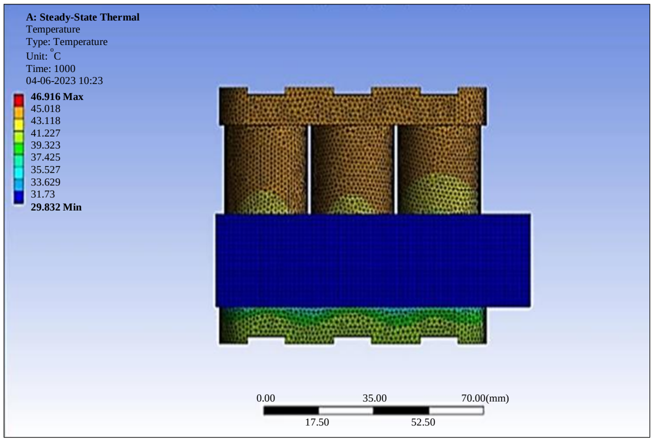
1. Internal heat generation inside the cells = 10,000 W/mm^3
2. Ambient temperature = 30°C
3. Convection heat transfer from the outer surface of the casing to the surrounding = 5 W/mm^2
4. Time = 1000 sec.

4.6. Thermal Analysis Results

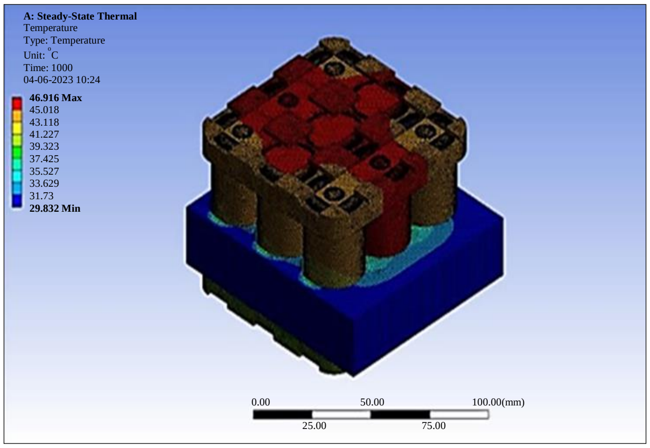
ANSYS 18.0 software was used for the analysis of the NMC battery. The following axial and radial heat dissipation results were obtained using the above boundary conditions. One thousand seconds of the time interval is used to dissimulate internal heat of 10,000 W/mm^3 inaxial and radial cases. The ambient temperature is taken as 30°C. The same results were compared, and the graph was plotted for better comparison. Thermal analysis for radial heat dissipation over center and outer surface is listed in Table 6 and shown in Figure 5 respectively.

Table 6. Temperature observations of radial case

Observations	Temperature
Outer Surface	30.5°C
Center	45°C
Minimum	30°C
Maximum	46.91°C

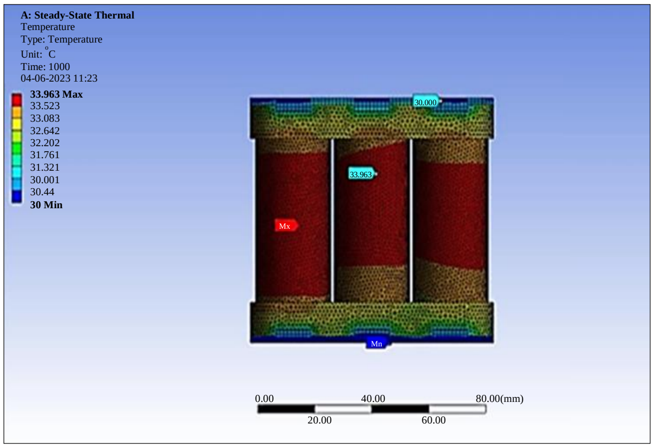


(a) At center

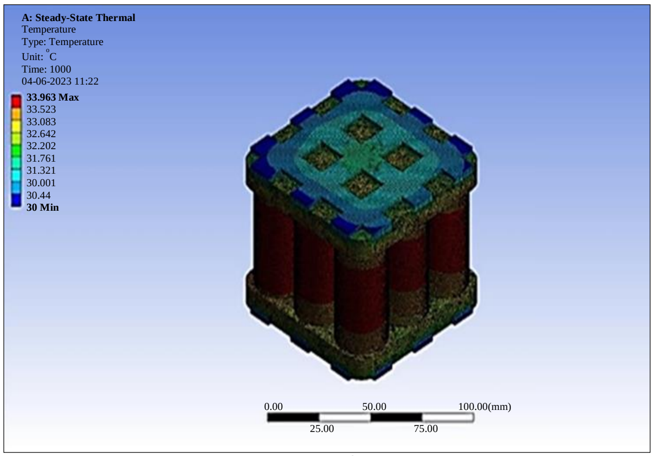


(b) Outer surface

Fig. 5 Thermal analysis for radial heat dissipation



(a) At center



(b) Outer surface

Fig. 6 Results of axial heat dissipation

The following results of axial heat dissipation were obtained. One thousand seconds of the time interval is used for dissipation of internal heat of 10,000 W/mm3. The ambient temperature is taken as 30^{o}C. From both results, it can be seen that axial heat dissipation is performing better than radial experimentally as well as in the FEA method. Thermal analysis for axial heat dissipation over center and outer surface is listed in Table 7 and shown in Figure 6 respectively.

Table 7. Temperature observations of axial case

Observations	**Temperature**
Outer Surface	30.5^{o}C
Center	34^{o}C
Minimum	30^{o}C
Maximum	33.96^{o}C

5. Results and Discussion

5.1. Experimentation Results

The experiment's temperature readings are plotted on a graph against time intervals to understand the results better and compare the two cases.

The graphs plotted to show that axial heat dissipation outperforms radial heat dissipation. Also, it clearly shows that the temperature-induced during charging is higher than discharging. Comparison of radial vs axial heat dissipation while charging and discharging is shown in Figure 7 and Figure 8.

5.2. FEA Results

Results of axial and radial heat dissipation were obtained. One thousand seconds of the time interval is used to dissimulate internal heat of 10,000 W/mm3 in axial and radial cases. The ambient temperature is taken as 30^{o}C. The same results were compared, and the graph was plotted for better comparison as shown in Figure 9. The graphs plotted to show that axial heat dissipation outperforms radial heat dissipation. The results obtained by FEA methods are very close to those obtained by the experimentation technique.

The results obtained from experimentation and FEA methods are tabulated in the Table 8 for comparison. The table values clearly show that FEA results are nearly equal to experimentation results values. In both cases, the axial dissipation is better than the Radial heat dissipation.

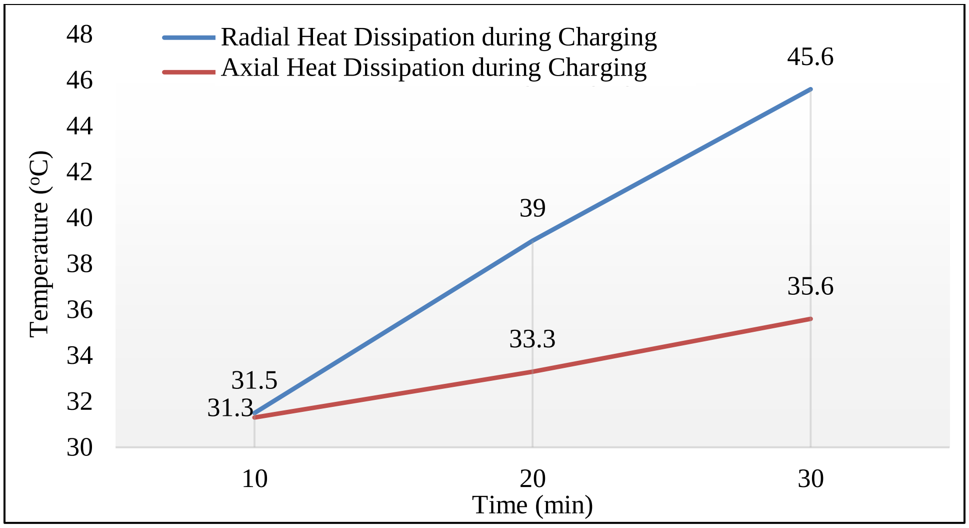


Fig. 7 Comparison of radial vs Axial heat dissipation while charging

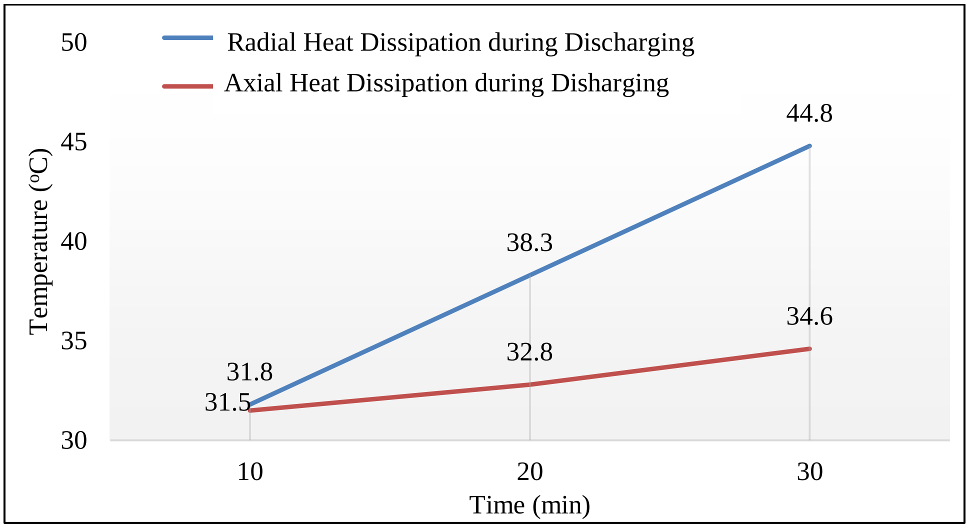


Fig. 8 Comparison of radial vs Axial heat dissipation while discharging

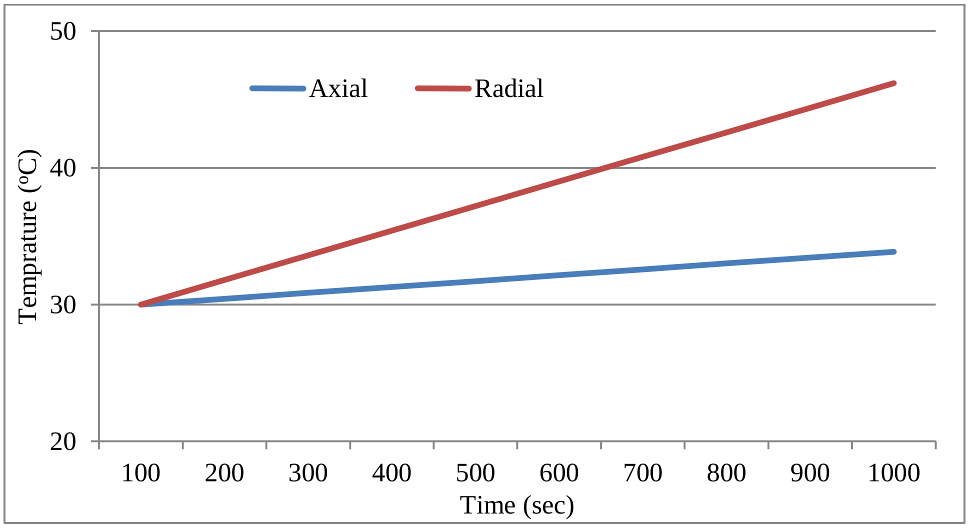


Fig. 9 Comparison of radial vs Axial heat dissipation by FEA method

Table 8. Comparison of experimental and FEA method results

Temperature (^oC)	Experimentation Method		FEA Method	
	Radial	Axial	Radial	Axial
Initial	30	31.3	30	30
Final	45.6	35.6	46.916	33.963

6. Conclusion

The results obtained from analysis and experimentation are matching to each other. Based on the comprehensive analysis of experimental measurements and computational simulations, it is concluded that the axial heat dissipation method is more effective than the radial heat dissipation method in Li-Ion batteries. The axial configuration offers superior thermal management, reducing temperature gradients and ensuring a more uniform heat distribution within the battery cell. These advantages lead to enhanced battery performance, improved safety, and prolonged lifespan. The findings of this research contribute valuable insights for the design and optimization of thermal management systems in Li-Ion batteries, facilitating their broader application in various industries.

1. The temperature rise during axial heat transfer is much lesser than radial heat transfer.
2. The axial heat dissipation method is more effective than radial heat dissipation.
3. As we have used the same conductivity of the material in both cases. It has more scope in the case of axial heat transfer to enhance the heat transfer rate by using the material's high thermal conductivity.
4. Temperature rise during charging was higher than discharging of the battery.

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