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Assessment of thermal characteristics in diverse lithium-ion battery enclosures and their influence on battery performance

Mahiban Lindsay[1], M. Emimal[2]
[1]Department of Electrical and Electronics Engineering, Hindustan University, Chennai, India
[2]Department of Electronics and Communication Engineering, Anna University, Chennai, India

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ABSTRACT

Battery technology is an emerging research domain within the automotive sector, with a focus on various battery chemistries such as Li-ion, LiFePO4, NMC, and NaCl, as well as specialized cells like LiSOCl2. These chemistries are crucial in advancing electric vehicle (EV) battery technology. Batteries are available in different packaging formats, including prismatic, cylindrical, and pouch designs, each tailored to diverse operational environments. This study investigates the impact of these various battery packages on overall battery performance. Additionally, it assesses the influence of temperature on battery efficiency, aiming to identify the optimal temperature range for maximum performance. A significant part of the research focuses on the development of efficient battery thermal management (BTM) systems, which are designed to control and maintain battery temperature within the desired range, thereby enhancing efficiency. The outcomes of this study provide valuable insights for improving the reliability and efficiency of EV batteries. These findings are crucial for ensuring optimal battery performance and safety across different field conditions. Automotive manufacturers and battery suppliers can leverage these insights to refine their product designs, ensuring the dependability and safety of EV batteries. By enhancing battery performance through improved packaging and effective thermal management, this research contributes significantly to the advancement of EV technology, making electric vehicles more reliable and efficient for consumers.

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Corresponding Author:

Mahiban Lindsay
Department of Electrical and Electronics Engineering, Hindustan University
Chennai, India
Email: nmlindsay@hindustanuniv.ac.in

1. INTRODUCTION

Lithium-ion batteries have become the prevailing choice for energy storage in electric vehicles due to their exceptional energy density, power density, minimal self-discharge rate, and extended lifespan when compared to other rechargeable batteries [1]. Nevertheless, the operational temperature significantly influences the physicochemical characteristics of these Li-ion batteries, impacting their safety, performance, and longevity [2]. Maintaining a narrow temperature differential of less than 5 °C between modules within a Li-ion battery pack is essential. Furthermore, Li-ion cells are engineered to function within a strict temperature range of 20 °C to 40 °C. Therefore, one critical aspect of electric vehicle battery systems is the thermal analysis of lithium-ion cells [3]. The fabrication of a lithium-ion battery cell encompasses three primary phases: electrode manufacturing, cell assembly, and finalization [4]. These phases involve multiple intricate steps, commencing with the coating of anode and cathode materials, progressing through component assembly, and culminating in cell packaging and testing. While there are variations in designs, such as prismatic, cylindrical, and pouch cells, the manufacturing procedures remain largely consistent [5]. Approximately 25% of the cost associated with Li-ion batteries can be attributed to production expenses. These batteries consist of essential components, including an electrolyte medium facilitating the flow of lithium ions between electrodes, a separator preventing electrode contact and short circuits, and two electrodes. An anode for capturing lithium ions during charging and a cathode for the same during discharging [6]. The cathode may comprise various metal alloys, while the anode is typically composed of graphite, often incorporating nickel, cobalt, lithium, and other elements [7]. Visible terminal tabs represent the positive and negative terminals, and the entire assembly is enclosed within a protective shell. By placing and interconnecting individual cells, a battery pack is formed, serving as a fundamental building block in electric vehicle power systems [8].

In the realm of vehicle power systems, a crucial technique is the management strategy for hybrid propulsion systems. This study introduces an initial management technique based on finite state machines for both battery/fuel cell and battery/supercapacitor/fuel cell systems. The management strategy has been tailored to accommodate the power capacities of the battery and supercapacitor [9]. Furthermore, an adjustment for the ideal oxygen excess ratio is proposed to enhance the net output power of the fuel cell. The study includes simulations and experimental validations using actual physical systems, with evaluation conducted under the urban dynamometer driving schedule to assess fuel efficiency and dynamic performance [10]. The results of both simulations and experiments demonstrate that the proposed strategy can ensure the necessary power for the majority of driving cycles. Over the last decade, there have been noteworthy advancements in energy storage technologies within the realm of hybrid power systems [11]. These developments have significantly influenced innovation, research endeavors, and potential avenues for enhancing energy storage technologies [12]. To establish a comprehensive understanding of hybrid power systems, this study conducts a quantitative analysis of all knowledge sources related to hydrogen energy storage, employing mathematical and statistical methods. A systematic search of the Scopus database was performed, employing predefined search criteria, to identify relevant publications on energy storage technologies for hybrid power systems [13], [14].

The temperature of electric vehicles varies depending on environmental conditions, and batteries play a crucial role in everyday life. They are utilized in various sectors, including electric vehicles, power plants, and renewable energy sources, aiming to reduce pollution and fuel consumption [15], [16]. This article explores cooling techniques to monitor and regulate battery temperature. An Arduino microcontroller continuously records the battery's temperature, providing insights into its health and aiding in prolonging the battery system's lifespan [17]. Such thermal management is highly beneficial in today's world, allowing for effective control of the battery temperature and enhancing overall system performance.

2. DIVERSE BATTERY ARRANGEMENTS

Three distinct battery arrangements are employed based on application requirements and operational feasibility. The primary objective is to conduct thermal analysis on these various battery configurations and identify their respective effects.

2.1. Cylindrical cells

Cylindrical cells, also referred to as lithium-ion battery cells with a cylindrical shape, find extensive use in consumer devices, electric vehicles, and renewable energy sources [18]. These cells are composed of key components, including a separator to prevent electrode contact, a positive electrode consisting of lithium cobalt oxide, a negative electrode made of graphite, and two terminals. Typically, an organic solvent containing lithium salt serves as the electrolyte [19]. The most common sizes for cylindrical cells are the 18650 and 21700, with their dimensions denoted by the numbers in their names (18×65 mm and 21×70 mm, respectively). These cells come in various capacities, voltages, and discharge rates to suit specific applications. Thanks to their high energy density and ease of series and parallel connection, cylindrical cells are widely adopted to fulfill the power requirements of various systems and devices.

2.2. Prismatic cells

Prismatic cells, also known as rectangular or square-shaped lithium-ion battery cells, are a popular choice in stationary energy storage systems, electric vehicles, and devices requiring high power output and energy density [20]. Unlike cylindrical cells, prismatic cells feature a flat, rectangular design that offers a larger surface area and greater design flexibility for constructing battery packs. These cells comprise a separator, a negative electrode, and a positive electrode enclosed within a flat, rectangular casing [21]. Typically, they employ a lithium salt dissolved in an organic solvent as the electrolyte. Prismatic cells come in various shapes and sizes, catering to diverse applications ranging from handheld devices to electric cars and grid-scale energy storage systems. They are engineered for rapid charging and discharging, delivering robust power output [22]. Their flat, prismatic shape allows for more efficient stacking, optimizing space utilization within battery packs. Additionally, prismatic cells are known for their ease of manufacturing and assembly, with a lower likelihood of leakage compared to cylindrical cells. However, due to their more intricate production process, they often come at a slightly higher cost.

2.3. Pouch cells

Pouch cells, also referred to as lithium-ion battery cells with a flat, pliable, and lightweight structure, are widely employed in consumer electronics, electric vehicles, and portable devices that demand exceptional energy density and flexibility [23]. These cells consist of a separator, a negative electrode, and a positive electrode enclosed within a thin, flexible, and heat-sealed pouch packaging. Typically, they utilize a lithium salt dissolved in an organic solvent as the electrolyte [24]. The pouch design offers superior design flexibility and a larger surface area for battery packs. Pouch cells are available in various shapes and sizes, ranging from compact versions for handheld electronics to large ones used in stationary energy storage systems and electric vehicles. They boast high power output, excellent energy density, and are engineered for swift charging and discharging.

3. ARDUINO IDE CONTROLLER

The Arduino IDE was employed for programming, enabling the display of temperature, current, voltage, and charge readings. This software facilitated the programming of an Arduino microcontroller board to acquire and present the required data. A pivotal aspect of this process involved coding for establishing communication between the microcontroller and multiple sensors, including those for current and temperature. Subsequently, after processing data from these sensors, the microcontroller exhibited the outcomes on a display, such as an LCD screen. Employing this approach, a simple yet effective system was devised for monitoring and presenting essential electrical characteristics. Experimentation with diverse sensors and display choices allowed for system customization to meet specific needs and requirements.

4. THE INFLUENCE OF DRIVE CYCLES ON BATTERY CELLS AND THERMAL EFFECTS

The performance of battery cells in various applications, such as electric vehicles, is strongly influenced by the drive cycles they undergo [25]. The Simulink model of drive cycles on battery cells, as shown in Figure 1, represents the specific acceleration, deceleration, and cruising patterns a vehicle undergoes during operation. These drive cycles can vary widely depending on factors like vehicle type, usage, and environmental conditions. One critical factor affecting battery cell performance during drive cycles is temperature. Temperature can have a significant impact on a battery's capacity, power output, and overall lifespan [26].

Figure 2 illustrates the effects of various drive cycles in relation to the performance impact of different cell configurations within the battery pack. This comparison highlights how different cell arrangements respond to patterns of acceleration, deceleration, and cruising, offering insights into optimal configurations for energy efficiency and battery longevity under varying operational conditions. Therefore, understanding how drive cycles affect battery cells in both temperature-controlled and non-controlled conditions is of utmost importance for optimizing battery performance and durability.

Figure 3 illustrates the charging characteristics of cylindrical cells, where the charging voltage starts at approximately 2.3 volts and gradually increases to 3.7 volts, covering the entire 0 to 100% charging range. This process takes approximately 330 minutes. Regarding prismatic cells, the charging characteristics are studied under two different temperature conditions, 40 degrees and 60 degrees, as depicted in Figure 3. At 40 degrees, the charging duration is notably shorter, taking only 263 minutes. In both temperature scenarios, the initial voltage is 2.4 volts, and the fully charged voltage exceeds 3.5 volts. For pouch cells, the charging behavior is also analyzed at 40 degrees. In this case, the charging time is 260 minutes. Similar to prismatic cells, the initial voltage at both temperature levels is 2.5 volts, and the full charge voltage exceeds 3.5 volts in both instances.

To analyze the discharging characteristics of cylindrical cells, a simulation is conducted at a temperature of 40 degrees Celsius. After 23 minutes, the voltage begins to decrease, marking the onset of the discharge phase. The resulting discharge characteristics are illustrated in Figure 4. The discharge duration remains consistent within cylindrical cells. In the context of prismatic cell discharging characteristics, the temperature decreases initiate after 91 minutes, and the time required to discharge the current remains unchanged, typically taking around 350 minutes to complete. As for pouch cell discharging characteristics, the voltage starts to decrease after 43 minutes at 40 degrees and experiences a sharp decline right from the outset. The discharge duration for pouch cells also remains unchanged, typically requiring approximately 295 minutes reaching completion.

Table 1 outlines a comprehensive breakdown of a vehicle's movement over time, capturing distinct phases such as idling, acceleration, deceleration, and steady-state motion. Each phase represents a specific operation in the vehicle's journey, with key metrics recorded to analyze the vehicle's performance and behavior. Positive values indicate acceleration (increasing speed), negative values indicate deceleration (reducing speed), and a dash (--) indicates no acceleration, meaning the vehicle is either idle or maintaining a steady speed. For acceleration and deceleration phases, the range of speed from the start to the end of the operation is provided. For idle and steady-state phases, a single speed value is given.

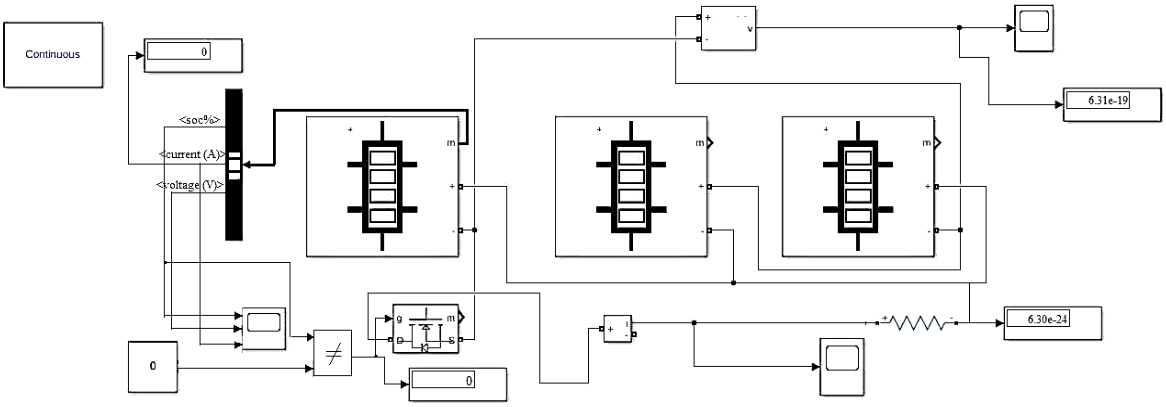

Figure 1. Simulink model of drive cycles on battery cells

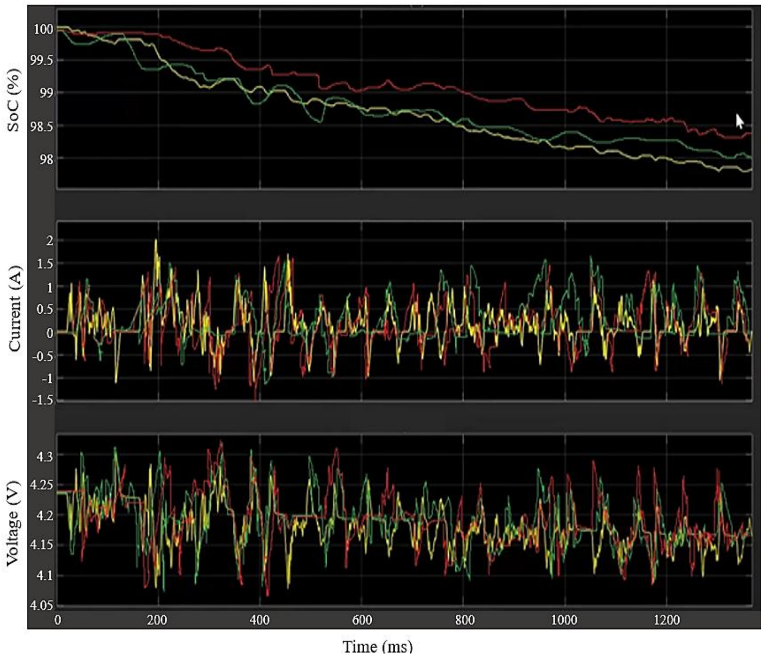

Figure 2. Effects of the drive cycle impact on cells

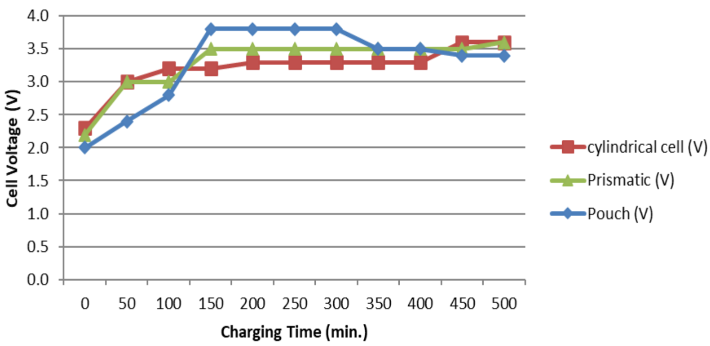

Figure 3. Charging characteristics for cylindrical, prismatic, and pouch cells

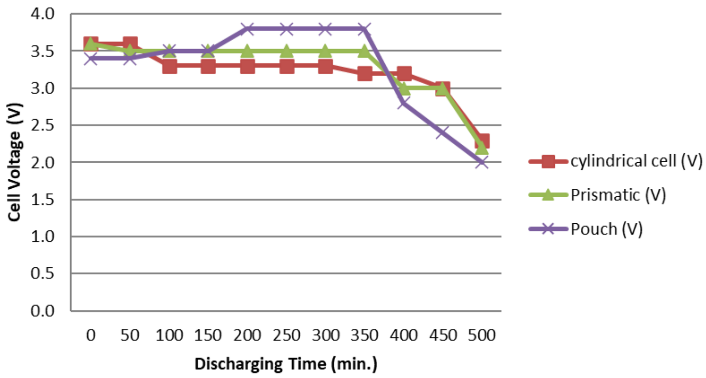

Figure 4. Discharging characteristics for cylindrical, prismatic, and pouch cells

Table 1. Drive cycle operations

No. of operation	Cycle	Acceleration 2 (m/sec)	Speed (Km/h)	Duration of each operation (s)	Cumulative time (s)
1	Idle	--		17	17
2	Acceleration	0.648	0-14	5.45	21.55
3	Acceleration	0.559	14-22	3.88	25.45
4	Deceleration	-0.626	22-13	3.85	29.50
5	Steady state	--	13	2.05	31.60
6	Acceleration	0.558	13-23	4.95	36.75
7	Acceleration	0.437	23-31	4.96	41.85
8	Deceleration	-0.558	31-25	2.90	44.75
9	Steady state	--	25	3.85	48.85
10	Deceleration	-0.557	25-21	1.75	50.60
11	Acceleration	0.449	21-34	7.78	58.70
12	Acceleration	0.317	34-42	6.90	65.50
13	Deceleration	-0.457	42-37	2.75	68.60
14	Steady state	--		6.85	75.70
15	Deceleration	-0.418	37-34	1.85	78.00
16	Acceleration	0.317	34-42	6.85	84.50
17	Deceleration	-0.455	42-27	8.85	93.70
18	Deceleration	-0.516	27-14	6.80	100.70
19	Deceleration	-0.558	14-00	6.68	107.60

The data in this table holds significant value for multiple aspects of vehicle analysis, including performance, safety, and efficiency. Table 1 allows for a detailed examination of how the vehicle accelerates and decelerates under various conditions. This can be useful for understanding the vehicle's capabilities, such as how quickly it can reach a desired speed or how effectively it can slow down. Different driving phases affect fuel consumption differently. For instance, steady-state driving at a consistent speed is generally more fuel-efficient than frequent acceleration and deceleration. By analyzing the time spent in each phase, it is possible to estimate fuel efficiency and identify opportunities to reduce fuel consumption. The data can reveal patterns in driver behavior, such as the frequency and intensity of acceleration and deceleration. These insights can be used to train drivers for more efficient and safer driving practices, which could lead to reduced wear and tear on the vehicle and lower operational costs. Deceleration phases are particularly important for understanding how a vehicle responds in situations where it needs to slow down quickly. By analyzing deceleration rates, it is possible to assess the vehicle's braking performance and overall safety in real-world conditions. Understanding the duration and impact of each phase in a driving cycle can lead to optimized driving strategies. For instance, minimizing the time spent in acceleration and deceleration phases could improve overall efficiency and reduce emissions, contributing to more sustainable driving practices. For engineers, the data provides valuable feedback on how a vehicle performs in typical driving conditions. This information can be used to improve future vehicle designs, making them more efficient, responsive, and safe for consumers. The outcome of the findings serves as a powerful tool for analyzing the dynamics of vehicle movement. It provides critical insights that can lead to improvements in performance, fuel efficiency, safety, and overall driving experience. The findings from such an analysis could inform decisions in vehicle design, driver training, and even traffic management strategies.

5. CONCLUSION

Pouch cells offer several appealing advantages that make them a favorable choice for specific applications. Their space efficiency surpasses that of cylindrical and prismatic cells. With a flat, flexible shape, pouch cells can be stacked and arranged in diverse configurations to accommodate the available space within a device. This proves exceptionally valuable in scenarios where space is limited or when a battery must be tailor-made to suit a particular device. Furthermore, pouch cells can exhibit a superior energy density when compared to other cell variants. This is attributable to their higher ratio of active material to the total cell volume. Consequently, pouch cells enable the creation of smaller, lighter batteries that offer the same energy storage capacity. Additionally, the manufacturing process for pouch cells is simpler and more cost-effective than that for cylindrical and prismatic cells. Pouch cells are typically produced by laminating multiple layers of electrode and separator materials together, often employing a continuous roll-to-roll process. This approach leads to reduced production costs and higher manufacturing yields. However, it's important to note that cylindrical and prismatic cells also boast their own unique advantages. Cylindrical cells are renowned for their durability and long cycle life, making them a preferred choice for high-drain applications like power tools and electric vehicles. In contrast, prismatic cells are frequently employed in larger batteries designed for stationary energy storage purposes. Ultimately, the selection of the most suitable battery type hinges on the specific demands of the application, considering factors such as space constraints, energy density requirements, and cost considerations.

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M. Emimal	✓	✓				✓	✓	✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

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Authors state no conflict of interest.

DATA AVAILABILITY
Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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BIOGRAPHIES OF AUTHORS

Mahiban Lindsay has been at Hindustan University, Chennai, since 2011. He graduated from the Faculty of Electrical Engineering at Anna University, Chennai, India. He received his master's in Power System Engineering from Anna University, Chennai, India. He is a recipient of a gold medal in Master of Power System Engineering from Anna University. He received his Ph.D. in Power System Reliability from Hindustan University, Chennai. Currently, he is a professor of Electrical and Electronics Engineering at Hindustan University. He is also a visiting faculty member at Anna University. He has coordinated international corporate training programs and delivered various engineering themes to industrial personalities in India and abroad. He delivered guest lectures and seminars in the areas of energy conservation, electrical safety, power systems, and control systems to various technical institutions. He can be contacted at email: nmlindsay@hindustanuniv.ac.in.

M. Emimal is currently pursuing a Ph.D. in the Faculty of Information and Communication at Anna University, Chennai. She received a bachelor's degree in Electronics and Communication Engineering and a Master of Engineering from Anna University, Chennai. Before commencing Ph.D. studies, she worked as an assistant professor for 5 years. She can be contacted at email: emimalm@ssn.edu.in.