Int. J. Electrochem. Sci., 17 **(2022)** Article Number: 220810, doi: 10.20964/2022.08.40

International Journal of
ELECTROCHEMICAL
SCIENCE
www.electrochemsci.org

Experimental Analysis of Thermal Behavior of a Lithium-Ion Battery using Constant Voltage under Different Cooling Conditions

Dhanaselvam Jayamohan[1,*], *Rukkumani Venkatasalam*[2], *Chinnadurai Thangam*[3]

[1] Department of Instrumentation and Control Engineering, Sri Krishna College of Technology, Coimbatore, India.
[2] Department of Electronics and Instrumentation Engineering, Sri Ramakrishna Engineering College, Coimbatore, India.
[3] Department of Mechatronics, Sathyabama Institute of Science and Technology, Chennai, India.
[*]E-mail: dhanzeeepcet@gmail.com

Received: 4 April 2022 / *Accepted:* 29 May 2022 / *Published:* 4 July 2022

Lithium-Ion Battery (LiB) plays a vital role in the applications from smart phone to Electric Vehicles (EV). In general, LiB is used as the main resource for primary as well as secondary applications because they have advantages such as long cycle life, slow self-discharge, high capacity, and low maintenance. In spite of its advantages, few factors such as protection circuit, efficient thermal management systems, battery material, cost and safety, degrade the performance of the LiB. So, to analyze the thermal behavior of the Lithium-ion battery, it is tested under air, water and oil cooling methods. A $LiFeO_4$ LiB with 3.2 V/ 6Ah capacity is used for the analysis. The nominal voltage and capacity are 24 V and 48mAh respectively. The temperature profile of the battery is tested under different temperature-cooling environments. The experimental results are validated using MATLAB and Minitab software. In MATLAB, the Simulink model is designed to operate a 5HP/240V/1750 RPM DC motor. In this analysis, charging / discharging characteristics, State of Charge (SOC) under different ambient temperatures and motor torque characteristics are obtained. The temperature influences under various cooling methods have to be analyzed using Minitab-2017 software. It is interpreted by Response Surface Methodology (RSM) and contour plot graphical analysis. It gives a very clear picture about the relationship between different factors such as charging / discharging voltage, various temperature points, temperature control with cooling and without cooling. Also, this analysis helps to identify thermal influence on the battery performance where the minimum temperature is very clearly visible. The safe operating temperature can easily be identified for various applications. This analysis aids in the prediction of extreme temperature conditions and provides solutions to protect the system. So, through this analysis, it is possible to identify the optimum operating temperature range of a Lithium-ion battery.

Keywords: Lithium-ion Battery, Cooling mechanism, RSM Analysis, thermal behavior

1. INTRODUCTION

Lithium-Ion Battery (LiB) is used in a variety of applications ranging from cell phones to electric vehicles (EV). LiB is commonly utilised as the principal resource for both primary and secondary applications because of its benefits, which include extended cycle life, slow self-discharge, high capacity, and low maintenance. It has been decided to develop the functional areas such as infrastructure, energy usage, charging station, emission of CO_2 and battery development. Despite its benefits, the LiB's performance is harmed by a number of issues such as its protection circuit, effective heat management systems, battery material, cost, and safety. To address these restrictions, several strategies for increasing and stabilizing battery performance during operation must be developed / improved. Among all aforementioned factors, temperature related problems are to be considered very seriously because it directly leads to safety. Due to this reason, LiBs have not been widely deployed commercially for many applications. So, the factors like capacity and power fade, thermal runaway, internal imbalance, low temperature performance are to be analyzed with different temperature ranges and environmental conditions.

The performance of the battery is highly temperature dependent. Various internal and external factors affect the performance of LiB and accelerates the degradation. Temperature is considered as a major limitation of LiB in which, both low and high temperature cause performance degradation [1-2]. So, maintaining the temperature within the limits is a crucial part in LiB to ensure safety, cost and lifecycle. It is stated that the optimal temperature range of LiB is 15°C to 35°C [3-4].

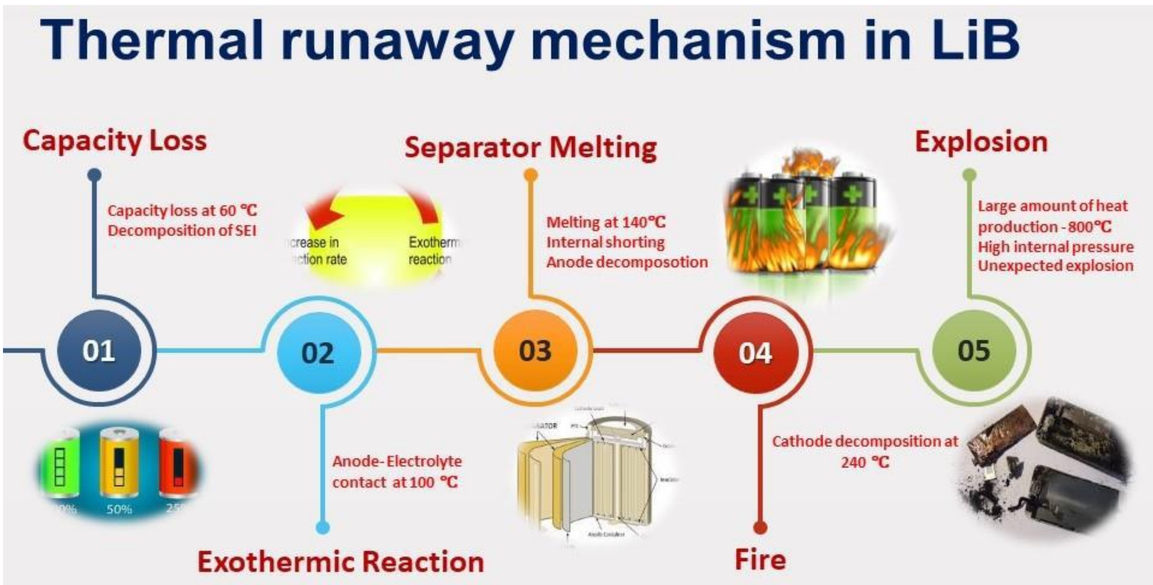


Figure 1. Temperature effects of Lithium-ion battery under different temperature

Environmental factors are also causes for temperature reduction and internally generated temperature from the battery is the main reason for temperature rise [5]. At low temperatures, internal resistance is increased due to low ionic conductivity [6]. In this situation, the charge transfer resistance will be three times more than the resistance at room temperature. At low temperatures, Lithium-ion diffusion is almost non-existent [7]. Other than the aforementioned factors, it is observed that low temperature operation leads to side reaction, slowdown in storage, electrode surface damage, faster aging rate, and capacity loss [8-9]. Analyzing temperature changes under various circumstances is a very crucial part in battery thermal management because it leads to harmful effects. The various effects are shown in the figure 1.

Some of the harmful effects are like, - temperature of the battery rises due to internal chemical reaction during charging / discharging, entropy changes and charge transfer process. The generated heat is distributed to the cell surfaces. The uncontrolled heat generation in the battery cells fastens the chemical reaction which leads to thermal runaway and explosion [10]. The heat generation is happening in the following order: (i) At 60°C - Capacity loss and decomposition, (ii) Exothermic reaction affects electrode material at 100°C, (iii) Separator melting at 130°C, (iv) Anode and cathode decomposition at 240°C, and (v) When the temperature reaches 800°C, it increases internal pressure and leads to emission of harmful gas, smokes, fire and unexpected explosion [6, 11].

To reduce the harmful reaction of the battery due to temperature, in LiB, measurement and control of it is need of the hour to improve the overall performance and also the safety. This can be achieved by designing of cooling system or improving the performance of Thermal Management System (TMS). When temperature is generated inside the battery it will be unevenly distributed among the cells. So, The TMS must ensure the management of high temperature as well as uneven temperature distribution [12]. It can be achieved by having a cooling system under high temperature. There are various methods employed for controlling the battery temperature. It includes air cooling, liquid cooling and phase change materials [13-15]. In general, air cooling and liquid cooling are used as a coolant and phase change materials are used as a coolant medium [16]. Designing of TMS depends on effectiveness of cooling, weight of the system, total production cost, complexity and, parasitic power consumption [13].

The following is how the work is structured: The second Section is devoted to a review of the literature on various cooling technologies and coolants. Air, water, and liquid cooling are all considered in this study, and the benefits and drawbacks of each are examined. The experimental setup for temperature management of Lithium-ion Batteries is described in Section 3. It also covers several methods of analysis, such as real-time experimental setup, MATLAB analysis, and Minitab analysis, all of which are necessary for the experimental study and validation. The findings of the experimentation are explained in Section 4. The analysis is based on experimental data in order to comprehend the changes in voltage and temperature caused by various cooling methods. For constructing a battery thermal model for a DC motor load under varied ambient temperatures, a MATLAB Simulink Model is employed. Finally, the Response Surface Methodology (RSM) and contour plot graphical analysis are performed using Minitab software. The temperature influence of air, water, and oil cooling systems is very readily recognized from this research.

2. LITERATURE SURVEY

Cooling methods play a vital role in reduction or controlling the temperature in LiB. Air and liquid cooling methods are the basic types. Based on the construction, the type of the cooling material, and nature of the applications, the cooling methods are chosen. Air cooling was employed for Honda Insight and Toyota Prius and it is found that this method gives effectiveness in temperature reduction up to 55°C [17]. After that, some improvement had been made for better thermal management. Yang et al [18-19] proposed air-cooling method with airflow ducts and Mohammadi et al [20-23] investigated with metal foam to improve the performance. Zhao et al [24] implemented air-cooling method to the cylindrical battery system and it was found that uneven temperature distribution was reduced. In addition to that, forced air cooling was also developed for drastic temperature reduction. But under high temperatures, the uniformity of temperature distribution was poor. However, adding exhaust fan and changing the flow channel will improve the performance to the certain extent. But the air-cooling method is not sufficient for electrical vehicle applications because the heat generation is more than the above-mentioned limit [18-25].

Another method is known as phase change material in which the heat absorption is good compared to the air-cooling method. Like the air-cooling method, the phase change material method is also simple, of less weight and temperature between the cells can be controlled effectively. The only drawback of this method is low thermal conductivity. By adding metal additives, thermal conductivity can be improved. But, in applications like electric vehicles, this method is also not sufficient because the heat generation will be in higher order [27-28].

Liquid cooling system is another method for maintaining temperature within a limit in the Lithium-ion battery. This method provides an efficient temperature control mechanism and it is used to prolong the battery cycle life. Also, the heat transfer coefficient, volumetric and mass flow rates are better than air cooling system. But, the limitations of this method are, that, it requires a large space which leads to more cost. The design of the liquid cooling system is based on the type, and performance of the coolant and type of the battery pack [29-32]. The effectiveness of the cooling can be improved by different methods such as cooling tubes, jacket construction and dielectric fluid.

For the better cooling mechanism, selecting of coolant medium plays a vital role and some of them for the better cooling mechanism, selecting the coolant medium plays a vital role and some of them are water, glycol, various types of oils, and acetone. [33]. Battery temperature control depends on the factors such as fluid flow rate, viscosity, density and thermal conductivity [29]. The rate of controlling is different for different coolants. For example, water is a fundamental liquid which can control the temperature upto 48.7°C under high flow rate [34]. But, the heat transfer efficiency of the oil is better than water, so, oil-based coolant can provide effective heat control [35]. In general, the viscosity of oil is greater and it requires more pumping power to move the heat transfer. But it is understood that under the same pumping power (KW) oil cooling provides 1.5 to 3 times better response than water [36].

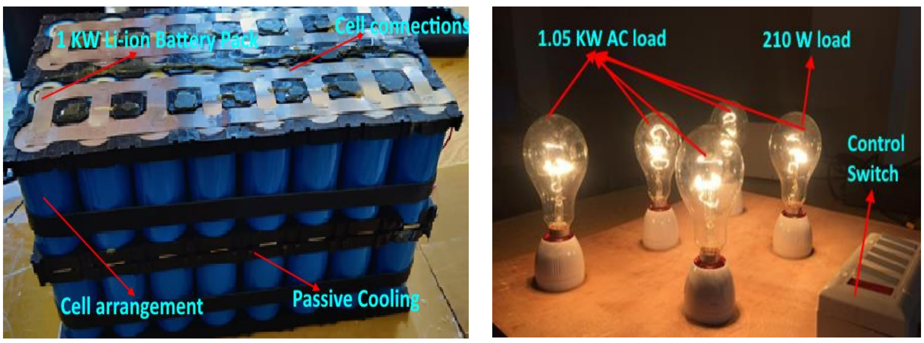
In general, the thermal conductivity is comparatively less for conventional air- and water-cooling methods, as they are insufficient to provide effective cooling. So, in-order to achieve this, high thermal conductive nano fluids are added with the conventional system to increase the effectiveness of cooling. When nano fluids with different ratio are used, the thermal conductivity can be varied and it enables better thermal management. Usually, Al, Ag, Al_2O3, Ni, CuO, Fe_3O_4 are used as nano particles [37-40] to enhance the thermal conductivity but it depends on particle size, type of the particle, fluid type, concentration and volume fraction. When water-Cu nano particle is taken into account, 0.1% of volume fraction makes thermal conductivity to increase up to 23.8% [41-44]. Other materials like Al_2O_3-water/glycol combination with 0.5% volume fraction increased the thermal conductivity. Other than this, $Al_2O_3/TiO_2/SiO_2$ mixtures show theatrically good results. When the particle size of the nano particles is reduced, it increases the Brownian moment and liquid layering activities which has high thermal conductivity [45-47].

From the literature survey, it is clearly understood that many researchers had discussed about different cooling methods to maintain optimum temperature in Lithium-ion battery. In this proposed work, an LiFeO4 - 3.2 V/ 6Ah capacity of 1KW LiB is tested for a constant lamp load of 1KW under different temperature conditions. Also, various cooling methods such as air, water and oil are employed for continuous monitoring control of cell voltage and temperature for the application mentioned above. From the experimental data, the change in voltage and change in temperature is found for the different cooling methods. The experimental data are validated using MATLAB Simulink and Minitab software. From the MATLAB simulation, when the battery is tested under different ambient temperatures from-30°C to +20°C, the change in cell voltage is analyzed. Based on this experimental data, Minitab software is used to analyze thermal influence under different cooling systems very clearly. For this analysis, Contour Plot and RSM are used and the optimal temperature and different coolant conditions are determined.

3. EXPERIMENTAL SETUP

3.1 Battery / Load Setup

The Thermal Management System is designed for 1KW LiB battery pack. A $LiFeO_4$ LiB with 3.2 V/ 6Ah capacity is used for the analysis. The nominal voltage and capacity are 24 V and 48mAh respectively. The total life of the battery is about 3000 cycles.



(a) (b)

Figure 2. Experimental setup of the proposed system. (a) 1KW battery system with cell arrangement (b) 1.05 KW lamp load which includes 210W of 5 lamps.

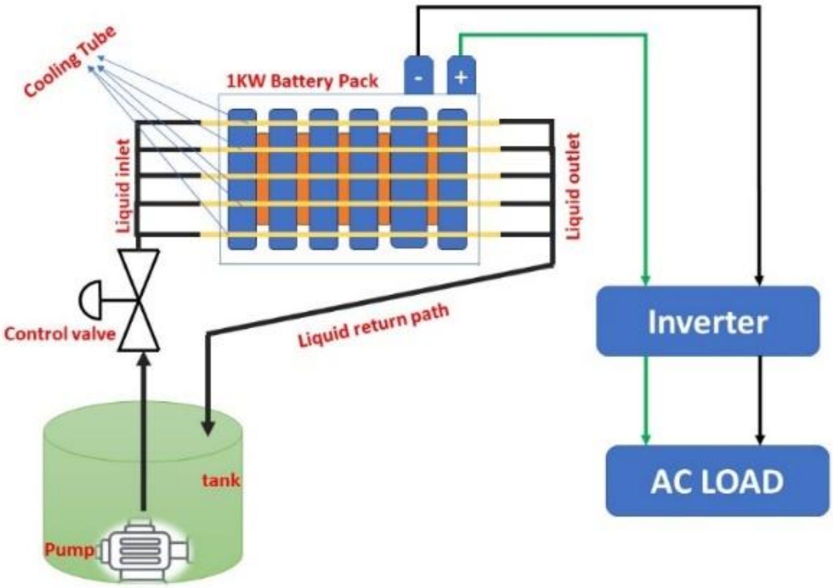


Figure 3. Temperature Management System

The operating temperature range is from 0°C to 60°C. To analyze the charging/ discharging performance the battery, 1.05KW AC load is used. The total capacity is included as 210W of lamp loads. To operate AC load, 1.5KW inverter is used to convert DC voltage into AC voltage. The entire experimental setup of battery system is shown in Figures 2- (a) & (b). The complete setup of the system is represented as block diagram in figure 3.

3.2 Cooling material

Liquid cooling system is taken into the consideration in this analysis because it has better temperature control when compared with other methods for electrical vehicle applications.

Table 1. Thermal physical properties of Air, Water and Oil [2,42-44]

Properties	Air	Water	Oil
Liquid Density (Kg/m^3)	875.5	999.975	875
Specific heat Capacity ($KJ/Kg.K$)	1.006	412	910
Thermal conductivity at 0°C (mW/mK)	24.35	0.598	0.1056
Thermal expansion coefficient	0.00369	0.042	0.00064
Boiling Temperature (°C)	26	99.97	196
Condensation temperature(°C)	27.6	100	260-370
Critical Temperature (°C)	55.9	373.94	-
Critical Pressure (atm.)	37.363	217.7	-
Density (Kg/m^3)	1.276	999.87	870
Dynamic Viscosity (Pas)	17.22×10^{-6}	8.9×10^{-4}	-
Kinematic Viscosity (mm^2/S)	0.0134	0.1684	75

Water, glycol, various types of oils and acetone are commonly used coolants for Lithium-ion batteries. It is known that glycol is a water-miscible coolant that can be used to conduct temperature from the battery. Ethylene glycol-water mixture is used for low voltage battery thermal management applications. When it is used for high voltage applications, it leads to safety issues. The temperature range of freezing and boiling points can be varied by having different ethylene glycol-water mixtures. It is possible to increase the freezing point to -3.4°C, -13.7°C and -52.8°C when 10%, 30% and 60% of ethylene glycol solution is used. In this work, air cooling and liquid cooling are considered for the temperature management. The two different combinations, water / glycol mixture and water / glycol / Nano fluid are used as coolant materials.

3.3 MATLAB Environment

The available capacity of the battery is measured as State of Charge (SOC). During charging and discharging it varies from 0 to 100%. Due to aging the SOC of the battery is affected. Temperature is an important factor which affects the SOC and leads to battery degradation, So, the SOC–temperature effect must be analyzed. This analysis is carried out using MATLAB Simulink library environment. A 64 bit, R2017a version of MATLAB is used for the simulation study.

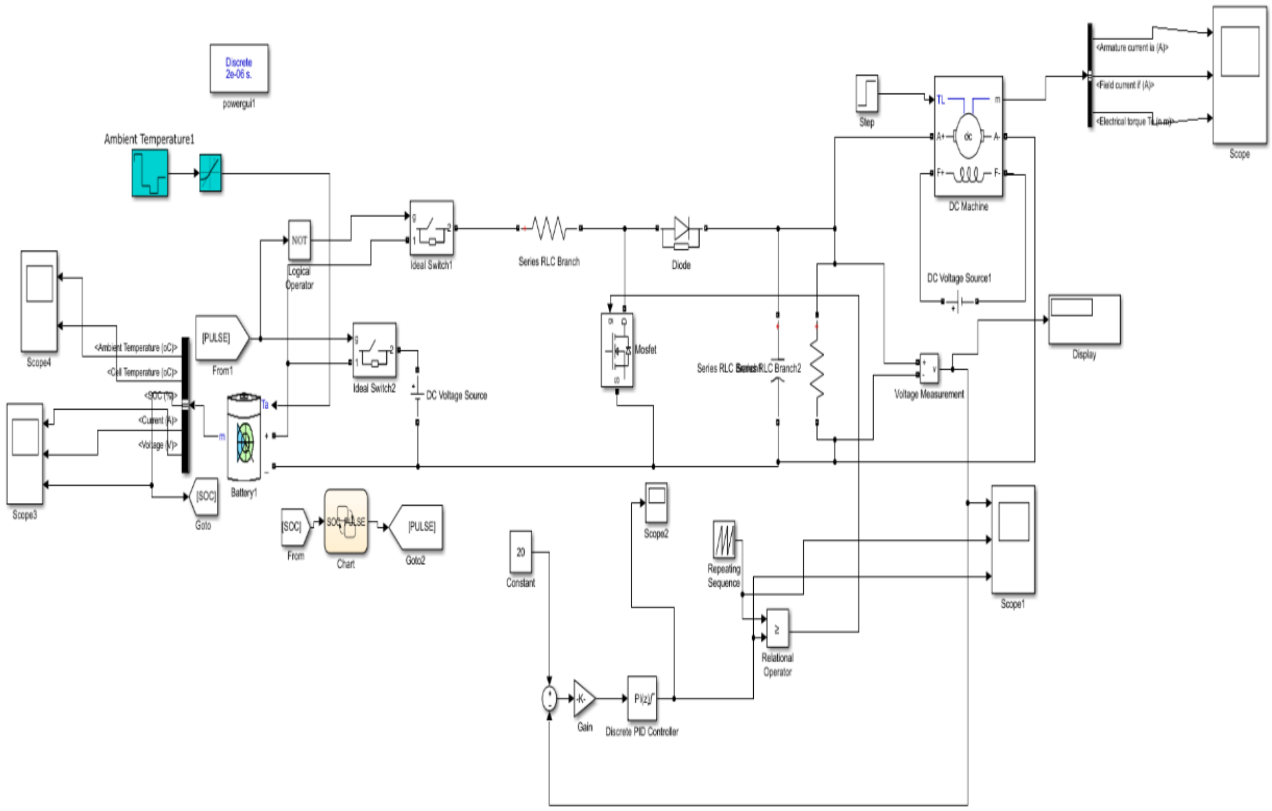


Figure 4. Simulink model for temperature effect of LiB.

Based on the proposed work, the Simulink model is designed to analyze the charging & discharging characteristics and temperature effects of 3.2 V/ 6Ah capacity Lithium-ion battery. The battery is connected with a DC motor load through DC-to-DC converter. Using this model, it is possible to analyze variation in the cell temperature with respect to environmental temperature. To analyze temperature variation, different ambient temperatures are set and the cell temperature is estimated. Also, the speed torque characteristic of the DC motor can be determined using this model and it is as shown in Figure 4.

The initial SOC is fixed as 80% and minimum SOC is set as 20% for the analysis. The simulated results are shown in Figures 9 to 12. The measurement of battery parameters such as voltage, current, SOC during charging and discharging, ambient temperature and cell temperature are also plotted.

3.4 Minitab Data Analyzing Tool

The data obtained from real time experimentation must be interpreted for various analyses. In this work, Minitab-2017 software tool is used for the analysis. It is done by Response Surface Methodology (RSM) and Contour Plot graphical analysis. It gives a very clear picture about the relationship between different factors such as charging / discharging voltage, various temperature points, temperature control with cooling and without cooling. By using this tool, it is easy to estimate the optimum temperature range under various working conditions because the Minitab consists of statistical procedure and mathematical analyses which are used to take effective decision on the temperature profile.

4. RESULTS AND DISCUSSION

In this proposed work, a comparative analysis is made between air, water and liquid cooling methods for the given Lithium-ion battery pack under different temperature conditions. Since it is an indirect cooling method, the cooling tubes or channels are fixed around the battery pack. In this work, initially air is used as a cooling medium and the analysis is made in terms of the effectiveness of air coolant on temperature control. Secondly, air is replaced by water for better improvement. Thirdly, to conduct more heat from the battery, Al_2O_3 Nano fluid is added with water / glycol mixture. And also, the effect of temperature on the SOC of the battery is analyzed with MATLAB simulation. The data obtained from the experiments is interpreted by the Minitab Statistical Analysis tool.

Table 2. Comparison of various cooling methods [2,26, 42-44]

Sl. No.	Thermal Management System	Points observed	Advantages	Disadvantages
1	Air Cooling	Forced natural Air Cooling is used. Variable inlet speed arrangement and increased	Less Components, low price. Air flow channels can improve the cooling efficiency compared to forced cooling.	Energy consumption is more. Due to special arrangements, system looks over-weighted. Lowest heat capacity.

		reversing frequency. Arrangement of pin fins along the direction of airflow. Changes in the design of inlet air flow direction.	Temperature controlled improved by increasing inlet velocity. Improvement in temperature uniformity.	
2	Liquid Cooling (Water & Oil)	Indirect cooling method Changes in the diameter of the cooling tube, inlet / outlet velocity, viscosity of the liquid, affects the cooling effects.	Optimization of cooling plate to improvise thermal conductivity. Optimized temperature control can be achieved using structural design change. Uniform temperature distribution can be achieved.	Slightly difficult to determine the optimal cooling plate for better performance. Maintenance cost is very high. Equipment cost is high. High energy consumption.

4.1 Experimental Result Analysis

The LiB is put through its paces during charging and discharging conditions at room temperature as well as at varied temperatures. The temperature is controlled using air, water, and oil cooling systems. The voltage and temperature are continuously measured in both the cooling and non-cooling environments to analyze the temperature impacts. The variations in battery voltage and temperatures under different time periods are obtained from the experimental analysis, and it is represented in the Figures (5) & (6).

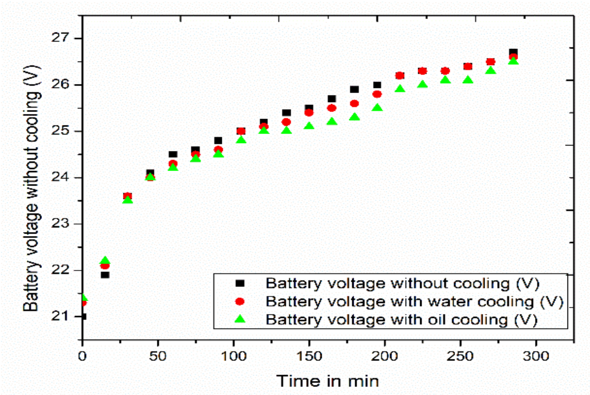


Figure 5. Voltage analysis with different timings

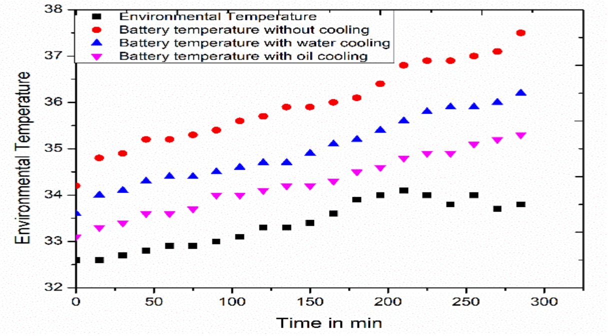


Figure 6. Temperature analysis with different timings

When the battery was operated for an extended period of time, the temperature was not fully controlled by air cooling. Heat generation might increase due to an increase in internal resistance. Overcharging and internal short-circuiting occur as a result. To mitigate this effect, a multi-channel coolant path is designed to increase the mass flow rate. Figure (4) clearly shows that ~~the~~ different cooling methods have an effect on the cell voltage level. Furthermore, even after running the LiB for 300 minutes, the voltage variation is very small in oil cooling.

Figure (5) clearly depicts the temperature effects of LiB under various cooling methods. The heat generation is not uniform over time under normal environmental temperature. The oil cooling method regulates the uneven temperature variation and internal temperature rise. According to the results of the analysis, the influence of temperature on the oil cooling method is very low when compared to other methods. The Table (3) compares various cooling methods.

Table 3. Voltage and Temperature changes under different Cooling methods: Charging

Sl. No	Type of Cooling	Change in Voltage (V)			Change in Temperature (°C)		
		V_{min}	V_{max}	$\Delta V = V_{max} - V_{min}$	T_{min}	T_{max}	$\Delta T = T_{max} - T_{min}$
1	Without Cooling	21	26.5	5.5	34.3	37.5	3.2
2	Water Cooling	21	26.2	5.2	33.5	35.6	2.1
3	Oil Cooling	21	26	5	33	34.7	1.7

In general, the overall heat generation is determined by the battery's entropic and ohmic heat generation during charging and discharging. The state of charge and life of the battery will be harmed primarily as a result of internally generated heat during discharging. The discharge is investigated in air, water~~,~~ and oil cooling environments. The variation in Voltage and Temperature is depicted in Figures (7) and (8). The variation of the Voltage change is observed depending on the cooling methods and it is understood that the oil cooling has the least variation. The Temperature profile is also investigated and Figure (8) shows that oil cooling has the greatest influence and that the temperature is controlled. So, oil cooling method is increasing the battery life by reducing the temperature during both charging as well as discharging conditions.

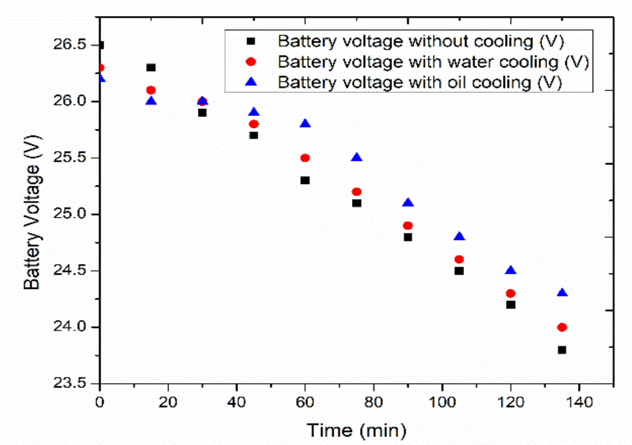


Figure 7. Battery voltage analysis with different timings during discharge

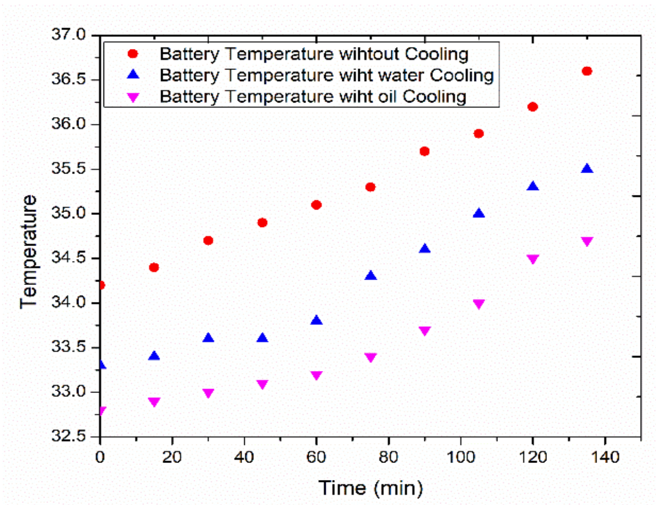


Figure 8. Battery cooling effects during different timings of discharge

Table 4. Voltage and temperature change under different cooling methods: Discharging

Sl. No	Type of Cooling	Change in Voltage (v)			Change in Temperature (°C)		
		V_{min}	V_{max}	$\Delta V = V_{max} - V_{min}$	T_{min}	T_{max}	$\Delta T = T_{max} - T_{min}$
1	Without cooling	26.5	23.5	3	34.2	36.7	2.5
2	Water cooling	26.3	24.2	2.1	33.2	35.3	2.1
3	Oil cooling	26.2	24.4	1.8	32.7	34.2	1.5

Based on Table (2), it is clear that oil cooling outperforms all other cooling methods used in the experiment. The change in voltage and change in temperature are minimum. As a result, for the constant load application of LiB, the oil cooling method for temperature control can be preferred. The analysis of the experiment results shows that during both charging and discharging, the oil cooling method takes precedence over other methods in controlling the parameters such as Voltage and Temperature.

According to various literature, a forced-air cooling system is used to analyze the thermal influences of cylindrical type LiFePO4 battery modules [19,22,23]. Whereas, the fixed air-cooling method is used in the proposed method for the rectangular 32 cylindrical cell package LiFePO4 battery module. The maximum temperature was kept constant at 45°C. The analysis is primarily concerned with the cell spacing. In another study, rectangular longitudinal fins were used to control temperature from 15°C to 35°C for low power applications. A mini-channel liquid cooling cylinder was used to further reduce the temperature effect. The maximum temperature remained constant at 40°C [30]. For a fixed mass flow rate of $1 \times 10^{-3}\ Kg/S$. The temperature difference remained constant at 3.49°C. Fluorinated liquid immersion cooling provides a maximum temperature rise of 34.5°C to some extent. It provides more precise temperature control than forced air cooling [23]. The temperature change is investigated in this proposed work both with and without cooling. During the charging conditions, the maximum temperature was maintained at 37.5°C, 35.6°C, and 34.7°C for no-cooling, air-cooling, and liquid-cooling, respectively. Similarly, the maximum temperature was maintained at 36.7°C, 35.3°C, and 34.2°C for no-cooling, air-cooling, and liquid-cooling, respectively, during discharging conditions.

4.2 MATLAB Simulation Results

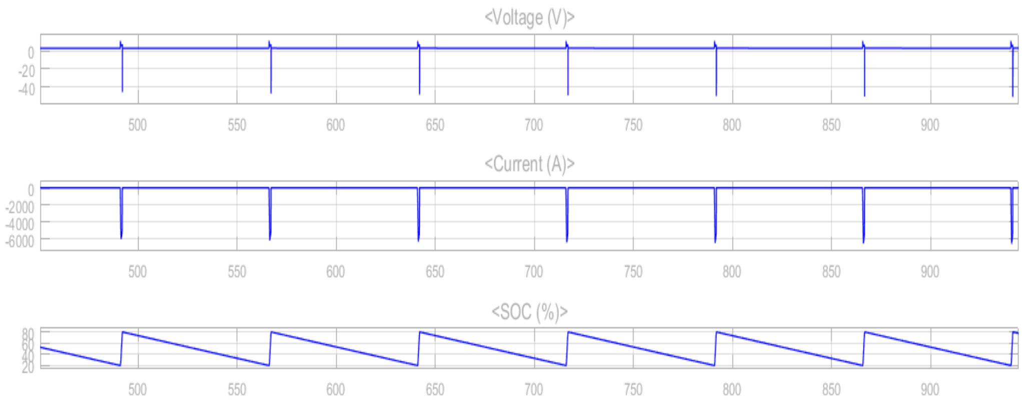


Figure 9. Charging & Dis-charging under +20°C to -20°C ambient temperature

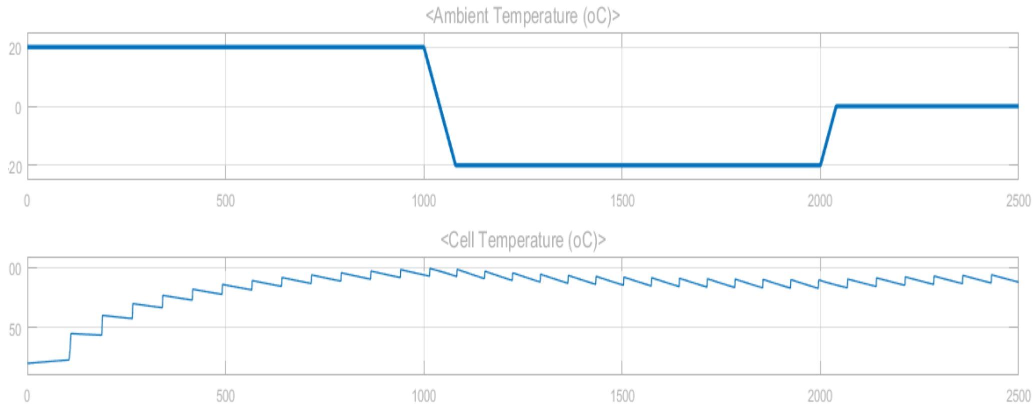


Figure 10. Cell temperature under +20°C to -20°C ambient temperature

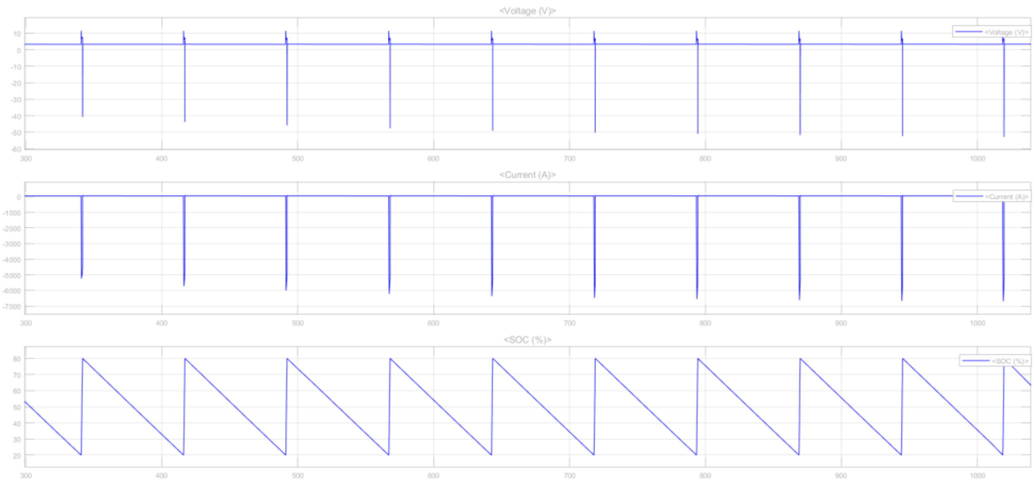


Figure 11. Charging & discharging under +30°C to -30°C ambient temperature

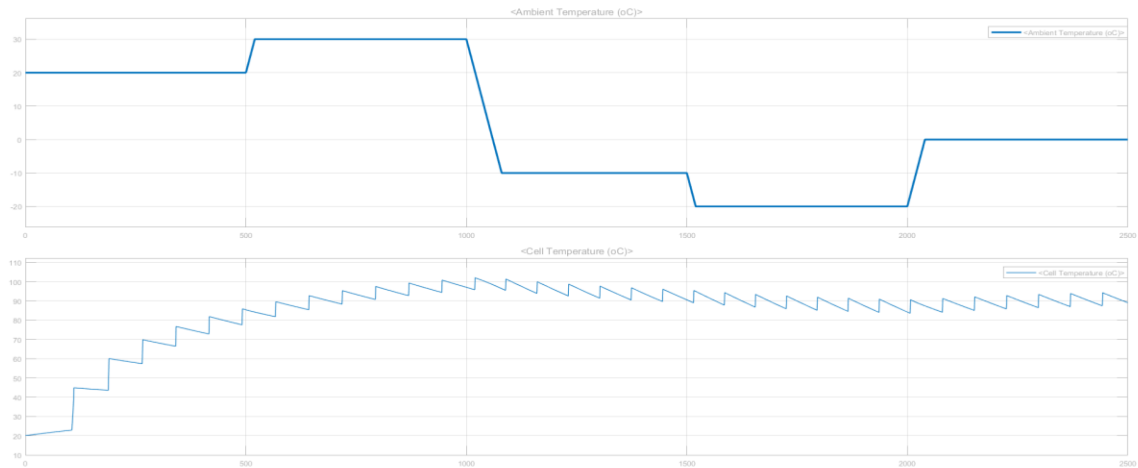


Figure 12. Cell temperature under +30°C to -30°C ambient temperature

From the simulation results shown in the figures 9,10,11 & 12, it is clearly understood that different operating temperatures lead~~s~~ to variation in cell temperature. Also, when the battery is operated for long periods, the cell temperature increases. At the same time, the variation in cell temperature leads to changes in charging, discharging voltages and current as well. This is because of increase in internal temperature~~.~~ In this simulation, the battery is subjected to different ambient temperatures and analyzed for varies parameter changes. The ambient temperature varied from -30^{0}C to +30^{0}C and the results show the variation in cell temperature. It is decided to run the simulation for 2500 seconds completely~~.~~ in which, internal cell temperature drastically increased for every 500S.

Many researchers created a simulation platform to gain a better understanding of the internal properties of LiB. According to them, the cell impedance was determined using an electrical equivalent circuit model to estimate SOC, SOH, temperature, and C-rate [48]. A 3KW motor is connected to a 7.4KW lithium-NMC battery for the performance analysis. The proposed work employs a MATLAB-Simulink model to drive a 5HP/240V/1750 RPM DC motor. This analysis yields charging/discharging characteristics, State of Charge (SOC) at various ambient temperatures, and motor torque characteristics. Also, the pulse discharge test was also performed at room temperature with 10% SOC [31,33,49]. SOC is accurately measured for a 3.7V LiB with a capacity of 2800mAh using 2nd order Thevenin's equivalent estimation methods as well as a fractional order extended Kalman filter [50, 51]. The proposed work's primary goal is to obtain cell temperature at various ambient temperatures and to observe changes in cell temperature.

4.3 Contour Plot Analysis

As a two-dimensional plot, the Contour Plot helps to understand the parameter variation of three the variables says x, y, z in which the influence of any third variable on other two will be analyzed. The plot shows that the points that have the same response value are connected to produce contour lines; from this the relationship between the factors can be analyzed. In this section, the analysis between Temperature and Voltage with various time intervals is done using Contour Plot. Also, the environmental temperature is taken into consideration for better understanding of thermal influence.

Table 5. Temperature effect of various cooling methods [2, 15, 26, 42-44]

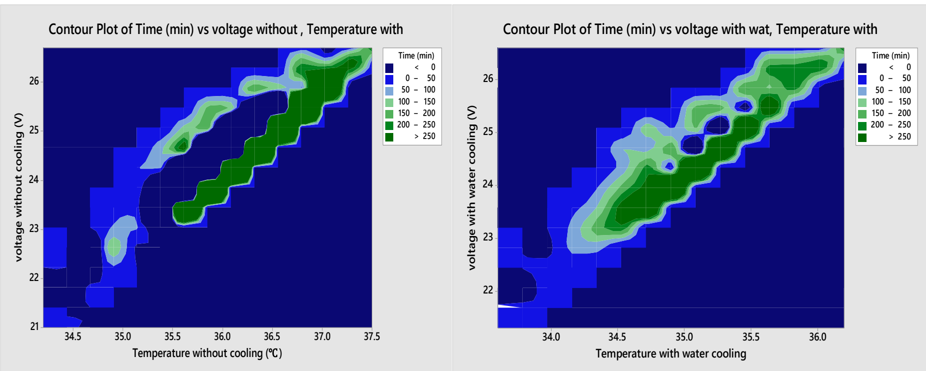
Sl. No.	Thermal management System	Points observed	Issues
1	Air Cooling	It can keep maximum temperature and temperature difference in ideal range. Improved inlet velocity and increased space between cells to reduce temperature rise. Temperature distribution was improved Heat generation rate was less than 3.75 × 105 W/ m3 Flow rate at 4 mL/s was found to be the best for water-cooling system Maximum temperature of the battery pack could be controlled below 48.7 °C The temperature difference between the batteries was within 5 °C	Cannot be applied for high current discharge. Needs more efficient BTMS. Uniformity in temperature control not maintained when temperature is increased beyond the limit. Not much suitable for fast-charging applications.
	Liquid Cooling	The best cooling performance can be obtained when the inlet temperature	Temperature difference upto 6.1°C.

	(Water & Oil Coolant)	is 18° C and the width of the cooling plate is 70 mm To reduce the pressure, drop low flow rate has been used in oil cooling To reduce freezing point of water, it is mixed with glycol 1.5 to 3 times better cooling efficiency	

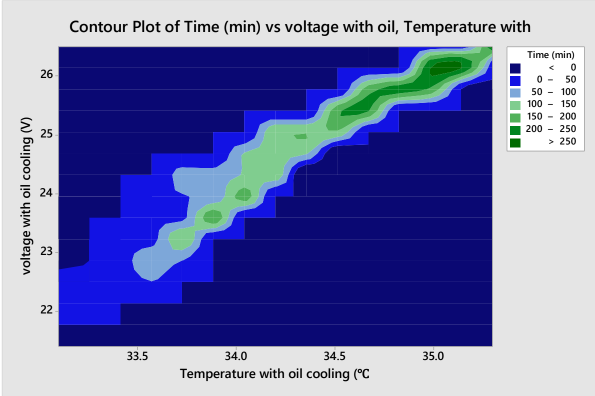
4.3.1 Contour Plot of Temperature effects over different time period

Figure 13 shows the influence of various temperatures over the voltage during different time intervals. This analysis interprets the changes of cell voltages and temperature under the presence of various cooling medium in the liquid cooling system. Figure 13(a) provides the effects of temperature on the battery when there was no cooling system employed. In this, the battery is operated under room temperature. Over a period of time, the cell voltage increases with increase in internal resistance. So, the generated heat affects the battery performance and different parameter variations are observed with various color changes. In this Figure13 (a), it clearly shows that there are no constant variations present and the influence of temperature is at large levels. From this, it shows that the battery is at an unstable state and there is a possibility of performance and safety issue.

Figure 3(b) shows that the battery is employed with water cooling system since water is considered as one of the coolant mediums. Under this operation, the influence of temperature on the battery performance is comparatively less. But, the generated heat in the battery over a period of time makes the water coolant, not to conduct more heat outside; rather it also gets heated up. However, the cooling effect is not that much effective and it directly affects the performance of the battery. And there are also few abnormalities of the battery that are observed. To optimize this problem, instead of water, a special cooling liquid is used and tested. In this, oil cooling provides a slightly improved performance over a specified period of temperature.



(a) (b)



(c)

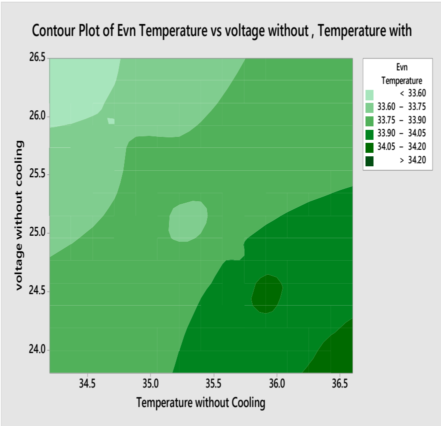
Figure 13. Contour Plot of time vs. battery Voltage and Temperature influence during charging are given as (a) provides without cooling effect of temperature and voltage variations (b) shows water-cooling influence over temperature and voltage (c) shows oil-cooling effects on temperature and voltage

This analysis is clearly shown in Fig.13 (c). Here, the temperature influence is drastically reduced when oil is the coolant medium. Under this condition, the stability of the battery is more and the battery shows improved performance. It enables the battery to work for a long life with higher cycle time. From this analysis, the results show different thermal characteristics over different time periods and also shows efficient cooling systems during charging conditions.

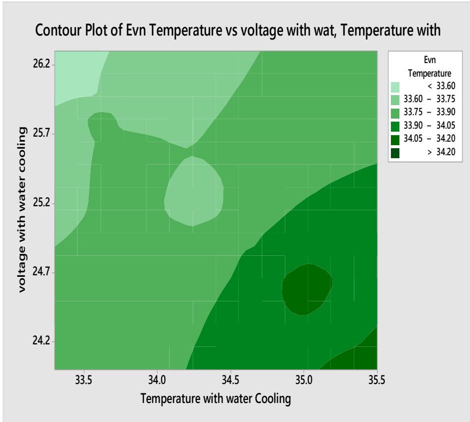
According to other researches, a 72.5 Ah NCM- Pouch Lithium-ion battery is triggered to thermal runaway using the hot plate heating method. The statistical software Minitab was used to analyse the thermal impact on battery performance and predict the thermal run-away trigger time [22]. The Response Surface Method (RSM) is used in the proposed work to analyze thermal influence and identify safe operating temperature ranges when the battery is used for fixed load operating conditions. This analysis interprets the changes in cell voltages and temperature caused by different cooling mediums in the liquid cooling system. Cell voltage increases with increasing internal resistance at room temperature. The best coolant was identified experimentally for various coolants such as gas, liquid, and nanofluid, and the maximum temperature distribution was analyzed using the Response Surface Method and the PSO algorithms to fix the optimized temperature for safe operation [53]. The RSM analysis concludes from the proposed work that the temperature influence was comparatively less when the coolant was water, but it was not as effective. The temperature influence is greatly reduced when oil or other liquids are used as coolants, and the battery is more stable for the applications.

4.4 Analysis of Environmental Influence

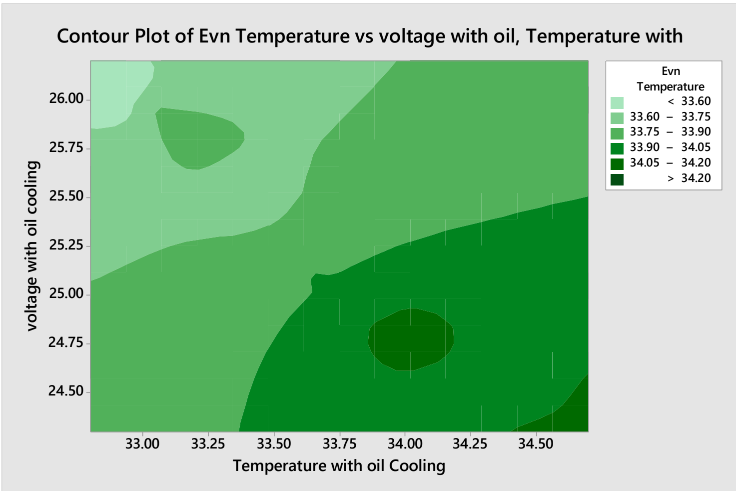
The variation of cell voltage with influence of temperature under various cooling medium during discharging of the battery is shown in the figures14 (a), (b) & (c). The heat distribution inside and outside of the cell is purely dependent on the type of coolant used in the liquid cooling system. The amount of heat generated and distributed will affect the overall performance of the battery. However, the selection of an effective cooling method for the battery is very essential, as each methods differs the total amount of heat carried out from battery.



(a)



(b)



(c) shows the oil-cooling effects on temperature and voltage.

Figure 14. Contour Plot of environmental temperature vs. battery voltage and temperature influence during discharge are given as (a) provides without cooling effect of temperature and voltage variations (b) shows water-cooling influence over temperature and voltage (c) Shows the oil-cooling effects on Temperature and Voltage

In this, Figure 14 shows the various thermal influences over different environmental temperatures with different cooling liquids. First the Contour Plot Figure 14 (a) shows the voltage and temperature variations of battery under no cooling condition. As time varies the influence is getting increased. The steady state of battery is changing over temperature. Likewise, in Figure 14(b) the stability of the battery is increased compared with no-cooling condition. The stability of the battery is higher in the oil cooling method, which enables the best operation of the battery. This change is clearly observed in Figure 14(c), that different temperature ranges in the battery are producing stable performance. But it still needs an improvement which can be obtained by choosing the best combination of cooling liquids.

The properties of LiB are alerted by environmental temperature. The performance of the battery varies due to temperature changes in different geographical locations. For the temperature range of -10°C to 30°C [54-55], the lumped battery model was proposed to estimate SOC accurately using recursive least squares and the Extended Kalman filter [55]. For the best estimation of battery parameters under varying ambient temperatures ranging from 0°C to 50°C, a Long Short-Term Memory (LSTM) – recurrent neural network is used [56]. The proposed work shows that when an oil cooling system is used, the temperature influence on battery performance is reduced. The oil cooling method increases battery stability, allowing for the best battery operation.

5. CONCLUSIONS

Lithium-ion batteries are the mainstay of numerous applications, particularly in the field of electric vehicles. However, the system's performance is good as long as the temperature is kept within the stipulated range of 15°C to 35°C. Extending the temperature range causes unanticipated events in both the battery and the system. As a result, a $LiFeO_4$ LiB with a 3.2 V/ 6Ah capacity was used in this study. The nominal voltage and capacity are respectively 24 V and 48mAh. The temperature analysis for a 1KW light load under various climatic circumstances is based on the experimentation. MATLAB Simulation and Minitab Simulation Tools are used to validate the data received from the experiment. MATLAB is used to run the setup for a 5HP/240V/1750 RPM DC motor load under -25, -20, 0, 20, 30, and 35-degrees ambient temperatures to analyze the variation in cell temperature. The temperature effect over different time periods is clearly analyzed using the Minitab tool from the Contour Plot. When oil is used as a coolant medium, the temperature influence is greatly reduced. Under these conditions, the battery's stability improves and its performance improves, enabling it to work for longer periods of time with a higher cycle time. The results of this analysis show different thermal characteristics over different time periods, as well as efficient cooling systems during charging conditions. The temperature influence is less in oil cooling compared to air- and water-cooling methods, indicating that the battery's stability is higher. Further improvement in temperature influence may be obtained by selecting different ratios of cooling medium and cooling materials.

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