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Thermal Investigation Of 18650 Nickel Manganese Cobalt Oxides Lithium-Ion Battery Pack

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Abstract - Due to growing climate change concerns driven by automobile emissions, the depletion of fossil fuels, and the rising cost of crude oil, electric vehicle (EVs) has become more popular as form of transportation. Energy storage systems are one of the key areas receiving intense attention in ongoing development of electric vehicle. While the energy storage systems for EVs are primarily lithium-ion batteries (LIB). Unfavorable operating temperatures can affect the safety, performance, and degradation of batteries. Therefore, it has become crucial to look further into the thermal behavior of li-ion battery. Using simulation (COMSOL) and experimental technique, thermal analysis of cylindrical li-ion batteries with nickel manganese cobalt oxides (NMC) chemistry is carried for 1C charge and discharge rate at atmospheric conditions (27°C). The simulation technique covers the measurement of surface temperature of battery cells with the help of heat generation rate as input and monitoring output temperature at multiple sensor locations. Utilizing experimental technique, simulation technique accuracy is validated. For 1C charge and discharge rates at atmospheric temperature, the simulation investigation technique suggested in this work forecasts the battery cell surface temperature with a minimum 92.3 percent accuracy during the whole load cycle. The research's thermal investigation can assist for designing suitable thermal management system as well as battery management system operating strategies.

Index Terms — Lithium-ion battery, Simulation technique, Experimental technique, Thermal management system, Electric Vehicle (EVs) and COMSOL

I. INTRODUCTION

The increasing popularity of electric vehicles (EVs) will likely take center stage in the future due to worldwide challenges with energy scarcity and environmental pollution [1]. With the globe depending more on renewable energy sources, EVs are the most appropriate solution for a clean, green environment to replace the conventional internal combustion engine technology with electric motors. The power battery system serves as the main power source of these electric motors. Due to their comparative higher energy and high-power densities, higher gravimetric, higher voltage discharge, lower self-discharge rates and volumetric energy densities, LIBs are best source of energy for an electric vehicle (EVs), outlasting other current battery technologies over the course of their calendar lives [2, 3].

Recent studies show that lithium-ion batteries (LIBs) will keep becoming better over the next few years and will continue to stand out from other batteries in terms of cost, safety, energy, and power capabilities. The development of LIB and EVs powered by LIB still faces significant obstacles related to thermal safety and degradation of LIB [4]. Nearly all cell materials experience a rapid drop in LIB performance and stability at the anomalous temperature range. Low temperature will cause lithium plating during rapid charging and discharging, which will greatly lower the battery capacity. High temperatures will speed up the harmful effects and deterioration of batteries [5]. For instance, the solid electrolyte interphase (SEI) layer on the anode grows more quickly at high temperatures during fast charging, becoming more porous and unstable [6]; also, manufacturing faults such holes in the separator may indeed be overheated [7]. According to Feng et al. [8], the local overheat is one of the abusive situations that can cause thermal runaway, along with mechanical, electrical, and thermal abuse. As a result, if the heat is not regulated, the battery could overheat or have a thermal runaway caused by an exothermic reaction and temperature increases beyond irreversible occurrences [9,10]. As a result, battery life will suffer, which is not good for EV owners. Therefore, in addition to being required to maintain a safe operating range, a battery thermal management system (BTMS) is also required to provide uniformity in temperature distribution for a battery pack's longer lifespan.

The highest temperature rises and the maximum temperature difference for battery pack are the two key factors used to assess the BTMS's performance. The temperature of all the cells must be kept constant between 20°C and 45°C to ensure optimal performance and to extend the life of the power battery. Under a wide range of C-rates, the maximum temperature difference between cells should be less than 5°C. C-rate [11], which is connected to the operational state of an EV, is the measurement of charge and discharge current in relation to its nominal capacity. The temperature gradient that exists across an operating cell can be described using the most recent key cooling coefficient metric that Gregory [12] suggested. It can advise a designer about the ability of heat generation and transfer, as well as how challenging thermal management would be in the cells selected in a pack.

The thermal investigation of 18650 lithium batteries with NMC chemistry is the emphasis of this paper. Using experimental and simulation techniques, this thermal investigation is carried out for charging and discharging rate of 1C at surrounding temperature of 27°C. The specifications of batteries chemistry investigated in this research are list down in Table I.

Table I. Specification of Cell

Geometry/Chemistry	18650 Lithium Nickel Manganese Cobalt Oxide (NMC)
Cell Material	$LiNiMnCoO_2$
Rated-Capacity (Ah)	3.5
Nominal-Voltage (V)	3.635
Mass of Battery	49 (in gms)
Specific-Heat	950 (in J/kgK)
Cell Volume	16540.49 mm^3

II. NUMERICAL INPUTS

Battery generates heat during charge and discharge load cycle. A portion of the generated heat is released into the environment, while the remainder increase the battery temperature. As a result, battery temperature can be reduced by increasing the release of heat to environment. Thus, it is critical to precisely construct the equation of energy, which includes generated and transported heat along with adequate boundary conditions in order to anticipate the correct temperatures during charge and discharge load. The equation of energy for measuring the battery inside temperature can be stated in the following way using the energy conservation law Eq. (1):

$$Q = \frac{d}{dx}\left(kx\frac{dTc}{dx}\right)+\frac{d}{dy}\left(ky\frac{dTc}{dy}\right)+\frac{d}{dz}\left(kz\frac{dTc}{dz}\right)+ m.Cp\frac{dTc}{dt} \quad \dots (1)$$

In above Eq. (1) m, Cp, Tc and t are the mass, specific heat, battery temperature and time respectively and battery thermal conductivities is represented by kx, ky, and kz in different directions. In Eq. (1), right side include conduction of heat in x, y, z directions and energy stored in the battery and left side indicates heat generation as a result of charge or discharge loads.

There are mainly two basic source of heat generation. The first is irreversible heat, which is caused by internal resistance of battery, and other is reversible heat, which is caused by a change in entropy as a result of a chemical reaction. As a result, generated heat due to charge and discharge loads can be written as below Eq. (2):

$$Q = I^2 R + I.T_C.EC \quad \dots (2)$$

Where R, I, and EC represents internal resistance, charge/discharge current and entropic coefficient respectively. Uniform temperature is considered in all directions within the battery to reduce computing work without affecting accuracy. The heat transfer rate is calculated using heat transfer from equation and volume [13,14].

B. Internal Resistance

Internal resistance exists whenever there is current flowing through a machine or electrical circuit and a drop in source voltage or source battery. When the battery is under load, this value influences how much energy (electrical) is burned away as heat (current flowing in or out of the battery). Greater energy is dissipated and converted to heat when there is a higher resistance. A lower resistance indicates that the battery is often more efficient, wasting less energy. In general, a battery's internal resistance is higher in cooler temperatures while lower in warmer conditions. A battery's internal resistance should ideally be zero. Because of this, when a battery is operating, all of the voltage is dropped over the component it is powering rather than across the battery itself. Batteries will always have some resistance. The internal resistance range must be monitored in order to restrict the amount of current that would flow in the case of an inadvertent short circuit. The internal resistance of a battery fluctuates depending on the battery's level of charge and temperature. Depending on the battery's charge level, the internal resistance changes. The capacity that is currently accessible for a cell is shown by its state of charge (SOC), which is a function of its rated capacity. The SOC's value might be anywhere between 0% and 100%. The cell is said to be fully charged if the SOC is 100 percent, and it is said to be completely discharged if it is 0 percent [15,16,17].As a result, the battery's SOC must be examined first. The SOC of battery can be determined as follows in Eq. (3);

$$SOC\ (t+1) = SOC(t) + \frac{1}{Cn}\int_{t}^{t+1} I(t).dt \qquad \dots (3)$$

SOC (t +1) and SOC(t) in above Eq. (3) are SOC of battery at time t+1 and t respectively and, I (t) and Cn are current at time t and battery capacity. Internal resistance at different temperature and SOC for all batteries are measured experimentally during charge and discharge testing. Fig. I display the surface plot of internal resistance for 18650 NMC batteries with relation to temperature and SOC.

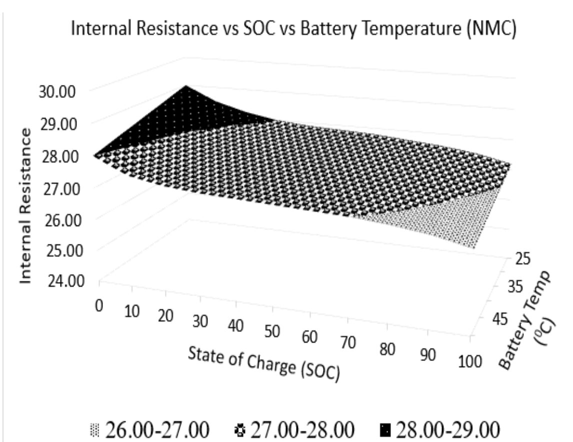


Fig. I – Surface plot of internal resistance for 18650 NMC batteries with relation to temperature and SOC.

C. Specific Heat

Specific Heat is a physical property of a material object. The specific heat capacity varies from one battery to other because of differences in materials, manufacturing processes, and internal structure. The temperature of the substance with a high specific heat must be raised using a significant amount of heat. It will give an indication of how much energy will be required to cool or heat an object of given mass by given amount. Furthermore, batteries have a complicated chemical composition, and the battery undergoes complex chemical reactions during charging, discharging, and ageing, resulting in a change in phase structure and on its electrodes. As a result, SOC, SOH, and temperature will alter the battery's specific heat capacity [18]. The specific heat values of the 18650 NCA, NMC, and LFP batteries are shown in Table I.

D. Entropic Coefficient

The thermal behavior of a lithium battery is influenced by the reversible heat source, especially during the early charge and discharge states. The entropic coefficient (EC) is one factor that influences the magnitude and direction of reversible heat [19]. The entropic coefficient measures the reversible change in the OCV in response to a change in the battery's temperature [20]. The value of the entropic coefficient varies depending on the SOC level and temperature. Entropy change in the electrochemical reaction is an important thermodynamic component in battery thermal design and heat control. The reversible heat generation of the battery has been discovered to account for a large fraction of the total heat generation rate [21].

III. SIMULATION TECHNIQUE

The battery is virtually simulated using the battery interface within the heat transfer in commercially available Multiphysics software i.e., COMSOL. The load cycle is defined using the operating voltage limits and the capacity rating of the battery. In order to model battery different geometrical and electrical parameters are required. The geometrical parameters like radius, height length and breadth of battery and along with that the electrical parameters like heat generation rate which is calculated using above equations where given. Due to this temperature of the battery is obtained as output. The temperature of the battery pack is found at different locations using sensors. Fig. II shows the location of sensors used to collect temperature data.

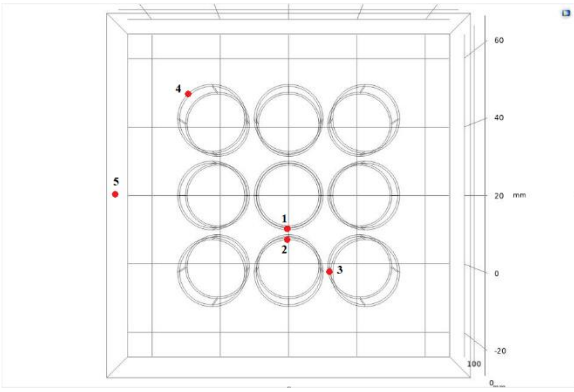


Fig. II – Sensor Location

IV. EXPERIMENTAL TECHNIQUE

Fig. III – Experimental Setup

In order to find the maximum heat generated in the battery, an experiment was carried out. To examine the thermal behavior of the dummy battery and further to confirm the simulation technique used for the thermal investigation, the temperature on the surface of the battery and cell with NMC chemistry were determined experimentally. A test setup that includes a power supply, battery, temperature sensor, DAQ system, and a PC for recording and monitoring was built to conduct experimental testing in the lab. In order to measure the subsequent rise in battery temperature, a power supply/load unit was connected to the battery and used to apply a charging and discharging load cycle. Utilizing a temperature sensor that was attached as shown in the figure and connected to DAQ, the battery surface temperature and the cell temperature were detected. The DAQ was additionally linked to the PC in order to record and track the battery's temperature during the charging and discharging cycle. The test setup's overview is shown in Fig. III.

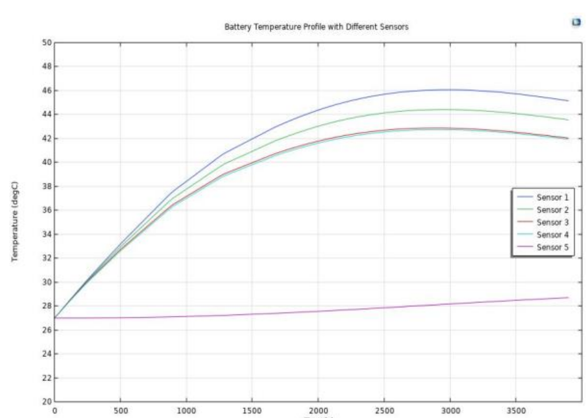
V. RESULT AND DISCUSSION

A. Boundary Conditions

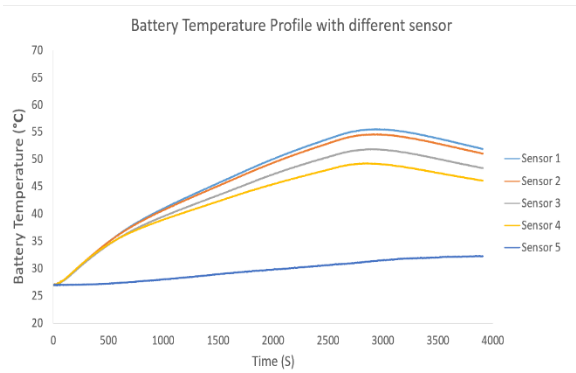
By using a charge and discharge duty cycle at atmospheric temperature conditions, the temperature was recorded in order to explore the thermal behavior of lithium-ion batteries. In order to explore thermal behavior and validate the simulation technique utilized in this paper, the same boundary conditions were applied in simulation and experimental techniques. During the charging process, a duty cycle that included charging with constant current (CC) till the voltage reached its peak and then charging with constant voltage (CV) till the current reached C/10 was employed. The duty cycle for discharging is similar to that for charging: constant current discharge till the voltage hits its lowest point, then constant voltage discharge till the current is reduced to C/10 of the battery's capacity. Both charge and discharge testing were carried out at 1C Charging/discharging rate at the atmospheric temperature conditions of 27° C.

B. Simulation Results

The temperature of the lithium-ion was simulated using COMSOL software. The Fig. IV shows the variation of temperature for different sensor placed at different places.



(a) Temp. profile of Battery pack (Charging)

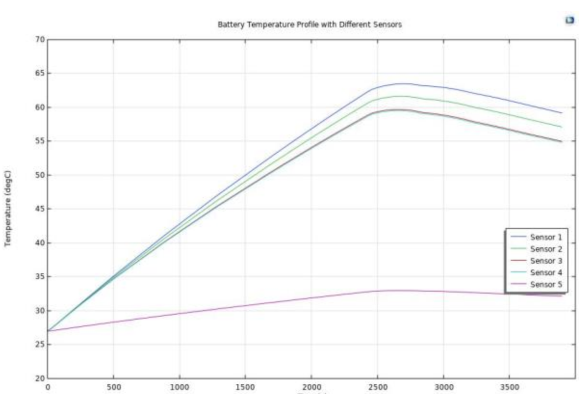


(b) Temp. profile of Battery pack (Discharging)
Fig. IV – Temperature profile (COMSOL)

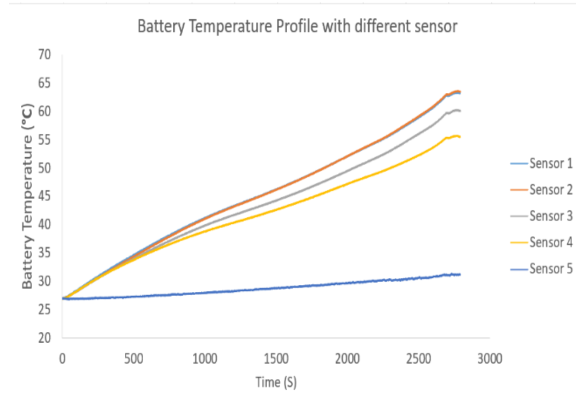
The maximum temperature obtained for 1C Charge loading cycle for all five sensors i.e., sensor 1, 2, 3, 4 and 5 are 53.97°C, 50.74°C, 52.44°C, 50.86°C and 31.34°C and for discharge loading cycle for all five sensors are 63.88°C, 62°C, 60.02°C, 59.85°C and 33.05°C respectively.

C. Experimental Results

According to the boundary condition, the temperature of an 18650 NMC Lithium-ion battery is experimentally determined for a 1C Duty cycle. Fig. V displays the battery sensor's observed temperature profile during charging and discharging settings at atmospheric temperature of about 27°C.



(a) Temp. profile of Battery pack (Charging)



(b) Temp. profile of Battery pack (Discharging)
Fig. V – Temperature Profile (Experimental)

The maximum temperature obtained for 1C Charge loading cycle for all five sensors i.e., sensor 1, 2, 3, 4 and 5 are 55.58°C, 54.63°C, 51.90°C, 49.32°C and 32.36°C and for discharge loading cycle for all five sensors are 63.36°C, 63.10°C, 60.29°C, 55.74°C and 31.38°C respectively.

D. Validation of Simulation Technique

The temperature recorded using simulation techniques is compared to the temperature acquired using the experimental technique to validate the simulation technique. The proposed simulation investigation technique done is validated with the experimentally measured data for 1C charging and discharging rate at atmospheric temperature condition of around 27°C. The comparison of sensor maximum temperature of lithium-ion battery measured with simulation technique with the temperature measured using experimental technique for specified charging and discharging rate at atmospheric temperature are given in table. From the comparison from the table, the maximum temperature of the simulation technique may be seen to be similar to the temperature profile of the actual technique and maximum deviation error observed in sensor temperature during the whole cycle of charge and discharge for atmospheric temperature of each sensor is respectively. The sensor temperature profile is well correlated for both methods for every charge and discharge rate. Therefore, the simulation method suggested in the study can forecast the temperature for an 18650 lithium-ion battery during a charging and discharging cycle with at least 92.3

percent accuracy under atmospheric temperature conditions. Below Table II and Table III show the maximum temperature and percentage error in the temperature measured using simulation technique as compared to experimental technique.

Table II – Error in Temperature profile (Charge)

	Simulation	Experimentation	Error
Sensor 1	53.97	55.58	2.983
Sensor 2	50.74	54.63	7.666
Sensor 3	52.44	51.90	1.029
Sensor 4	50.86	49.32	3.027
Sensor 5	31.34	32.36	3.254

Table III – Error in Temperature profile (Discharge)

	Simulation	Experimentation	Error
Sensor 1	63.88	63.36	0.814
Sensor 2	62	63.10	1.774
Sensor 3	60.02	60.29	0.449
Sensor 4	59.85	55.74	6.867
Sensor 5	33.05	31.38	5.052

VI. CONCLUSION

Experimental and simulation techniques were used to conduct a thermal investigation of the 18650 NMC lithium-ion battery. Battery temperature was measured at a 1C charge and discharge rate under 27°C atmospheric conditions. Further simulation technique that was proposed was confirmed by comparing the temperature values obtained using the simulation technique and the experimental technique. The simulation technique proposed in this paper include the calculation of heat generation rate using internal resistance, Entropic Coefficient and charge/discharge current. The following is the study's primary finding:

1. The temperature profile of the battery for entire charging duration is different from the temperature profile of discharging and the maximum temperature during discharging is much more compared to that of charging with same C-rate.
2. For all the sensors in the battery, good correlation of the temperature profile between both the simulation and experimental technique is observed for charge and discharge rate at atmospheric temperature condition. The simulation method put forward in this study can forecast temperature with at least 92.3 percent accuracy throughout the whole charging and discharging cycle for a 1C loading rate under conditions of atmospheric temperature.
3. For the same charge and discharge rate the temperature of outer most sensor i.e., sensor 5 on the battery outer surface is much lower than the temperature of the inner sensor i.e., sensor on the cells like sensor 1, 2, 3 and 4 during entire charging and discharging cycle.
4. The maximum temperature of middle cell is marginally higher than the temperature of other battery cells for same charge and discharge rate.

The simulation technique discussed in this paper can be used in order to measure temperature of 18650 NMC lithium-ion battery at any charge and discharge rate and at any surrounding temperature. The 18650 NMC lithium-ion battery's thermal investigation, carried out as part of this study, may be valuable in choosing the battery management system's operating strategies as well as choosing the thermal management system and optimizing it.

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