A model-based approach for temperature estimation of a lithium-ion battery pack

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***Abstract*— Temperature is an essential factor that substantially impacts lithium-ion batteries' cycle lifetime, capacity, safety, and heat loss. The present investigation analyses the influence of the lithium-ion battery cell's current rate on its temperature and thermal behaviour. The experiments were fulfilled at different discharge and charge cycles with different current rates. In this study, the thermal behaviour of a lithium-ion battery was analyzed at different current rates by employing a model-based approach from MATLAB. A correlation was seen between the current rate of the lithium-ion battery and the most remarkable temperature growth. The results would produce a more robust understanding of the temperature evolution of the lithium-ion battery cell for various applications. A smaller temperature was seen on the upper part of the lithium-ion battery pack.**

Keywords— lithium-ion battery pack, temperature estimation, a model-based approach

I. Introduction

There are growing concerns over the environmental, climate, and health impacts caused by using non-renewable fossil fuels. Electric vehicles can significantly reduce fossil-fuel consumption and relieve environmental pollution. However, a universal acceptance of low-cost electric vehicles is highly dependent on developing a highly efficient energy storage device with high energy and power densities, long cycle and calendar life, and low prices [1,2].

Among various energy storage devices, rechargeable batteries, especially lithium-ion batteries, are the most mature technique and have the most significant potential to meet the requirements for electric vehicles. Lithium-ion batteries have been prominent in portable electronics and are expected to be widely used in high-end applications such as electric vehicles. However, the energy density of current lithium-ion batteries technology is still relatively low, the charging capability is still not fast, and the cycle/calendar life is not long enough to meet the requested car life. In addition, safety and appropriate thermal management are other issues of the current lithium-ion batteries, especially in large-scale applications such as electric vehicles [3-6].

Comprehension of heat generation behaviour during discharging and charging a lithium-ion battery is essential to developing superior thermal management systems for lithium-ion batteries. The performance and behaviour of commercial lithium-ion pouch cells were determined by employing an isothermal battery calorimeter. It was concluded that immense growth in the lithium-ion battery temperature through the cell's surface was found on the lithium-ion battery cells surface [7].

Throughout the discharge process, electrical power is withdrawn from the lithium-ion battery and generated heat transferred from the lithium-ion battery. The aforementioned is vice versa throughout the charging process. The thermal behaviour of lithium-ion cells throughout discharge and charge at different current rates was investigated. Several experiments were accomplished in an adiabatic environment by employing an accelerating rate calorimeter. The impact of entropy variation on generated heat was lower at more enormous current rates. The aforementioned caused a more significant irreversible heat throughout discharging and charging at big current rates [8].

The heat loss modelling of lithium-ion batteries was done. In addition, the influencing parameters, such as the working temperature, state of charge, and current rates on the lithium-ion battery's heat generation rate, were determined. When the operating temperature was 50 °C, the heat generation amount was approximately the same as 20 °C at the lower current rates and increased comparatively toward big current rates. The heat generation level increases with the increase of charge and discharge current rates. The non-uniformity of the temperature distribution on the lithium-ion battery cell's surface overreaches 10 K, as was reported by the experimental data [9].

In [10-12], the influential parameters that affect the contributions of irreversible and reversible heating were determined. It was concluded that the heat of mixing rose at bigger discharge rates and was considered a consequential contributor to lithium-ion batteries' heat generation at discharge rates greater than 1C. The increased efficiency at the cycles with bigger charge and discharge current rates could be connected with raised lithium-ion battery overpotentials at bigger current rates. The increase in heat generation at the cycles with bigger charge and discharge current rates could be connected with reversible and irreversible heat generation and heat mixing. Both irreversible heat generation and reversible heat generation are a function of current. Notwithstanding, their contribution could be different at different charge and discharge cycles [10-12].

The heat of phase change is another source that contributes to the heat generation of lithium-ion batteries. Nevertheless, it has been chiefly disregarded in literature. The rise in irreversible heat generation at big current rates is attributable to raised over potential [13].

The surface temperature of the lithium-ion battery at different working temperatures was determined. It was concluded that the lithium-ion battery cell's most significant temperature at the end of the discharge and charge cycles depends almost linearly on the charge and discharge currents. A slight deviation was seen at specific currents from this linear trend. A considerable decrease in slope was not seen by decreasing working temperature. This linear correlation might arise from the relation between different parameters such as current, energy loss, temperature, and the lithium-ion battery cell's internal resistance. [14].

A systematic technique was employed to investigate the temperature effects. In this investigation, discharge-charge experiments were accomplished using the Maccor system, and the heat generation data was gathered through an isothermal calorimeter. It could be seen that the lithium-ion battery heat flux evolution correspondent to discharge and charge currents. It can be concluded that the heat generation inside lithium-ion batteries leads to the non-homogeneity of the surface temperature. The maximum temperature was found on the lithium-ion battery cell's upper part neighbouring the tabs. The minimum temperature was found on the nether portion of the lithium-ion battery cell. This finding can acknowledge the significant quantity of heat flux in that region. The heterogeneous temperature distribution attributable to interior losses in the lithium-ion battery cell could be decreased by putting the terminals on the opposite side of the lithium-ion battery cell [15].

Electric vehicles should work in different conditions, such as high temperatures in the summer and low temperatures in the winter. These temperature oscillations could intensely influence lithium-ion battery-powered vehicles' durability, driving range, and performance [16]. Consequently, it is essential to study the influence of working temperature on lithium-ion battery thermal characteristics to develop effective thermal management systems to lengthen the lithium-ion battery systems' output capabilities and lifetime.

The principal difficulty in lithium-ion battery thermal management is accurately estimating temperature and heat generation in lithium-ion batteries throughout discharging and charging. The oscillations in heat generation rate, temperature, and efficiency at different operating temperatures and current lithium-ion battery rates challenge additional research to better comprehend the heat generation mechanisms of lithium-ion batteries.

II. BATTERY MODEL

A diagrammatic of the lithium-ion battery model that was employed for the remaining part of this investigation is illustrated in Figure 1. The mathematical equations are taken from battery model in MATLAB. This model was selected attributable to its simplicity in characterizing behaviour of an electrochemical system. To develop the model for lithium-ion batteries electrical parameters were considered for the battery. The state of charge-dependent open circuit voltage and resistance values including R1 and R2 were incorporated into the lithium-ion model. The open circuit voltage values of lithium-ion batteries were determined by charging and discharging the batteries. The battery model from MATLAB was used for simulation and modelling of the lithium-ion battery pack.

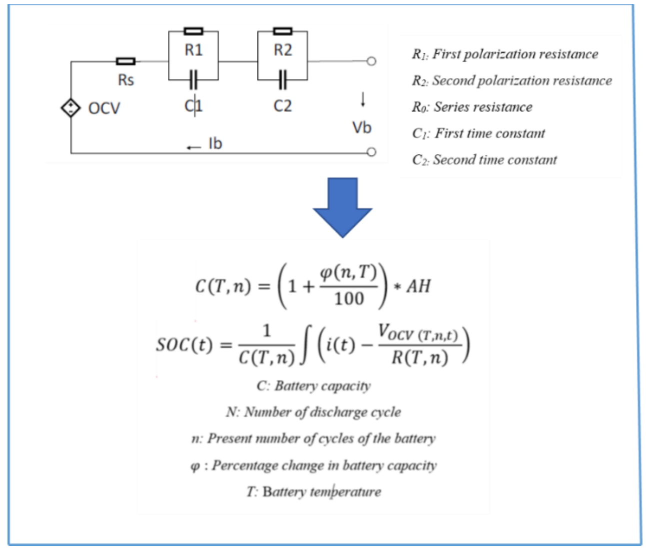
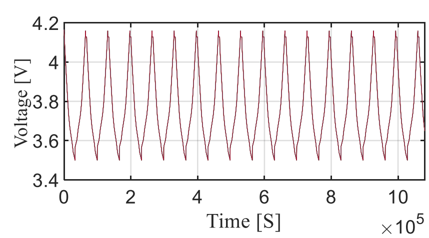


Figure 1. Procedure for determination of battery model.

III. RESULTS

A constant current charge and discharge profile was applied to the lithium-ion batteries, as shown in Figure 2. A schematic of the lithium-ion battery pack and battery pack model in MATLAB is illustrated in Figure 3. As can be seen, there is thermal insulation on one end, and the other end is exposed to the surroundings. The recommended model was constructed on MATLAB Simulink, which is significantly advantageous for comprehending the thermal phenomena of lithium-ion batteries in a model-based manner. According to the recommended model's comprehension of the lithium-ion battery's thermal behaviour, temperature-control strategies for lithium-ion battery packs could be developed. Simulation results of the lithium-ion battery pack are demonstrated in Figure 4.



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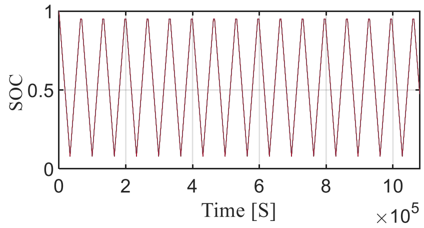

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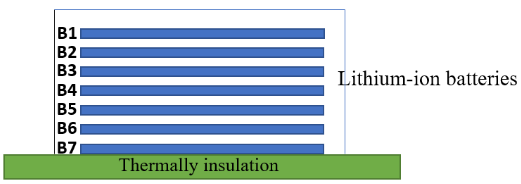
Figure 2. Constant current charge and discharge profile applied to the lithium-ion batteries.

This configuration illustrates that the heat transfer rate was more significant at the top part of the lithium-ion battery pack. This finding presumably results from more excellent heat transmission via the surroundings. It could be seen that the temperature of the lithium-ion batteries lessens with the environment temperature and raises with the current. Accordingly, the temperature enhances all over the lithium-ion batteries with bigger transferred heat. The aforementioned might acknowledge the explanation; the lithium-ion batteries' electrical system is principally changeable regarding temperature variations.



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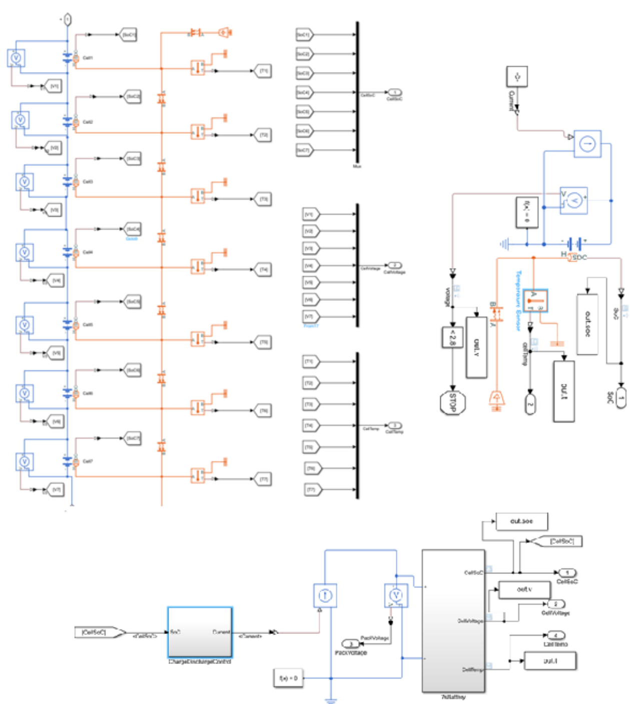

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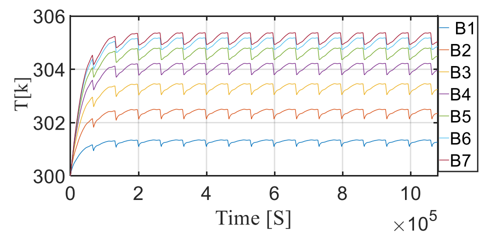
Figure 3. (a): A schematic of the lithium-ion battery pack. (b): Lithium-ion battery pack model in MATLAB.

Lithium-ion batteries have a heat generation boundary with individual compounds and materials as a function of operating temperature. Besides, it varies for different current rates. In addition, an immense current leads to more significant energy loss, which causes bigger temperatures. The lithium-ion batteries' heat flux and generation at the charging termination are lesser than discharge. Nevertheless, the heat generation is approximately identical between charging and discharging at the commencement. This finding might be due to the increase of the lithium-ion battery's terminal voltage, and the reversible heat takes up the heat while the lithium-ion battery is charging [14].



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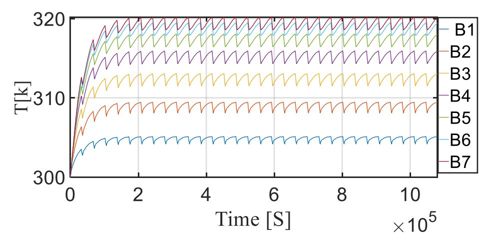

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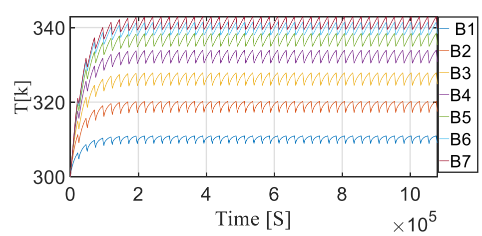

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Figure 4. Simulation results of the lithium-ion battery pack (a): 0.5 C, (b):1 C, (c):1.5 C.

While the lithium-ion battery discharge ends, the heat produced within the lithium-ion battery must go to zero. Accordingly, the presence of mixing heat could be found by investigating and evaluating the lithium-ion battery's heat loss characteristics in the discharge termination [17]. The internal resistance of lithium-ion batteries is the principal source of irreversible heat. These essential parameters are dependent on temperature. Preceding research on lithium-ion batteries has presented a significant dependency on lithium-ion batteries' internal resistance to temperature [18]. The irreversible heat produced during discharge is more significant than the charge [19].

Heat generation level at a definite temperature could be approximated. Heat generation is proportionate to the temperature. For all cases, heat generation during discharge cycles is bigger than during charge cycles. The aforementioned may correspond to the higher inner resistance of the lithium-ion battery during discharge. Notwithstanding, a distinguishable variation in the lithium-ion battery's heat flux was evident from the charge and discharge process.

Furthermore, a considerable increase in the temperature was seen for the lithium-ion batteries near the thermal insulation, indicative of a decline in their performance as the working temperature was raised. The cooling of the lithium-ion battery provides a restricted temperature growth to stop further exothermic reactions. Consequently, the heat generation could be controlled. The aforementioned can prevent thermal runaway. It can be concluded that the lithium-ion battery cell cannot be an acceptable nominee for a system that requires significant thermal safety, especially throughout ultra-fast charging/discharging, without a well-designed thermal management system.

IV. CONLUSION

In this study, the thermal behaviour of a lithium-ion battery was analyzed at different current rates by employing a model-based approach. The lithium-ion battery cell exhibited a considerable temperature increase, especially at bigger charge and discharge current rates, which demonstrated it as comparatively not the most satisfactory alternative from the thermal safety perspective without a proper thermal management system, especially under high working conditions. Those mentioned earlier affirm a proper consideration in designing a thermal management system for lithium-ion batteries, especially in a hot climate. The most significant temperature was found more adjacent to thermal insulation. The outcomes enable us to comprehend the impact of current rates on the lithium-ion battery cell's temperature through a straightforward method.

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AUTHORS' BACKGROUND