Theoretical modelling of heat generation in batteries of electric vehicles for various operating environments

Jay D Patel¹, Rajesh S Patel²
¹Assistant Professor, Ganpat University, Mehsana-384002, Gujarat, India ©
²Associate Professor, Pandit Deendayal Petroleum University, Gandhinagar-382421, Gujarat, India
Corresponding author E-Mail: jaydpatel1992@gmail.com;

Abstract. Due to high efficiency, cycling life, and specific energy, the Lithium-ion battery has been the best-favored selection for the Electric Vehicles (EV's) despite high cost. The performance of the battery pack is strongly dependent on the operation condition of the EV's and the environment. Under the extreme operation and environmental conditions of the battery, the rate of heat generation is very high which adversely affects the dissipation rate, decreases the battery life, and sometimes leads to the explosion and fire (i.e. thermal runaway). In electric vehicles, the battery thermal management technology plays a crucial role when the temperature of the cell rises exponentially during the operating environment. The temperature, therefore, between (15 to 35 °C) should be controlled. Our work presents the modeling of heat generation in the battery pack under various operation conditions. The parametric studies have been conducted to study the effect of battery operation conditions on heat generation rate and battery pack temperature. This study would be very useful in the selection of battery thermal management technology to control the battery temperature to retain the optimum condition.

Keywords: Electric Vehicles (EV), Battery Cooling, C-rate, maximum battery cell temperature, maximum battery cell temperature difference

1. Introduction
Electrical Vehicles (EVs) have witnessed rapid evolution with ongoing developments in automobile sectors and favorable government policies [1]. Nowadays, there is an enormous demand for EVs in the automobile sector due to the growing sensitivity of various governments towards a cleaner environment. Battery cells are sources of electricity for EVs that produce electricity by electrochemical reactions during charging and discharging cycles. For battery packs in EVs, various battery kinds, dimensions, and capabilities are available. Batteries are an essential component of electric cars, which requires utmost attention at the time of design [2]. The output and life of the battery are susceptible to environmental factors, charging conditions, and vehicle operating conditions [3]. For proper operation, the battery has to work in a strict atmosphere. Since the working of the batteries is quite temperature sensitive, running a battery within the range of temperature is very critical [4].

Batteries produce vast quantities of heat as the operating conditions become extreme. If an appropriate Battery cooling system is not used in EV's to efficiently evacuate the heat, the temperature of the battery cells may raise. The increase in temperature will intensify the chemical reaction, which will further increase the production of heat. If this continues for a prolonged time, the battery pack may reach thermal runaway conditions [5]. For that, a Battery cooling system is employed to dissipate the generated heat during the operation.
It is very essential to design and develop an appropriate Battery cooling system that increases the efficiency and effectiveness of EVs. The design of the Battery cooling system depends on the operation condition of EV’s and batteries and its effect on battery pack temperature and battery life. Hence it is very essential to develop a theoretical model for parametric studies on the consequence of operation conditions on the rate of heat generation and temperature of battery pack.

2. Heat generation in Battery cell
Li-ion battery performance and lifespan depend on the thermal condition of the battery cell. Since the thermal behavior of the battery cell is closely related to the rate of heat generation within a battery cell, it's important to calculate the heat generation for different operating conditions. The reversible heat and irreversible heat is mainly responsible for heat generation in battery cells [6]. The heat generation rate in the battery cell depends on the electric current(I), the open-circuit voltage (U), and battery cell voltage (V) and is calculated by Eq.1.

\[ Q = I(U - V) - I \left( T \frac{dU}{dt} \right) \] ................................................................. Eq.1

The factors which influence the heat generations in the battery cell are:
- The charging/discharging current. High solicitations result in an increase in battery temperature due to the dominating result of the Joule effect [7].
- The Depth of Discharge (DOD), which is related to the energy quantity which leaves from the battery.
- The battery temperature, the electrochemical reactions are accelerated and the internal resistance decreases when the temperature of the battery is increased [8].
- The state of Health (SOH), the amount of quality of a battery compared to its ideal condition [9].
- Available capacity [10].

The charging/discharging current plays a crucial role in heat generation compared to other factors which is evaluated by C-rate which is explained in the upcoming section 3.

3. C-rate
C-rate represents the rate at which a battery is discharged compared to its maximum capacity. If the whole battery is discharged by the discharge current in 1 hour, it’s discharging at a 1C rate. If the same
battery is discharged by the discharge current in 2 hours, it's discharging at 0.5C rate. If the same battery is discharged by the discharge current in 30 minutes, it's discharging at a 2C rate, and so on.

C-rate is dependent on the speed of the vehicle, gradient of slope, and number of seated persons. C-rate can be calculated from the driving conditions. Compared to the gradient of the slope, and the number of seated persons, the speed of the vehicle has a significant effect on C-rate.

The speed of the vehicle, gradient of slope, and number of seated persons influence the electric power consumption from the battery pack.

The total force required to drive a vehicle is calculated by Eq. 2

\[ F = F_r + F_d + F_g + F_a \]  \hspace{1cm} Eq.2

Where \( F_r, F_d, F_g, F_a \), and \( F \) represents the rolling force, drag force, gradient force, acceleration force, and total force required.

Electric power required to drive a vehicle is calculated by Eq. 3

\[ P_{ele} = \frac{F \times V}{\eta} \]  \hspace{1cm} Eq.3

Where \( P_{ele} \), \( V \), and \( \eta \) represents the electric power required, velocity of vehicle, and conversion efficiency of electric motor.

Effect of C-rate on electric power consumption is calculated by below Eq. 4 and 5.

\[ I_{spc} = \frac{P_{ele}/V_{BP}}{N_{CP}} \]  \hspace{1cm} Eq.4

\[ C - rate = \frac{I_{spc}}{C_{bc}} \]  \hspace{1cm} Eq.5

Where \( I_{spc}, C_{bc}, V_{BP} \), and \( N_{CP} \) represent the specific current, battery cell capacity, voltage of battery pack, and no. of battery cells in parallel.

3.1 Effect of speed of vehicle on C-rate
The effect of the speed of the vehicle on the C-rate is shown in Figure 3.1. As the speed of the vehicle increases, the C-rate increases rapidly. The C-rate is increased from 0.75C to 2.5C when the vehicle is accelerated from 60 kmph to 120 kmph.
3.2 Effect of road gradient on C-rate
C-rate increases linearly with the slope of the road. C-rate increases from 1.2C to 1.82C when slope varies from 2° to 20°. The effect of the slope of road on C-rate is shown in Figure 3.2.

3.3 Effect of seated person on C-rate
According to the number of people seated in the vehicle, C-rate linearly increases. C-rate increases from 1.04C to 1.13C when the number of people varies from 1 to 5. The effect of a seated person on C-rate is shown in Figure 3.3.
Figure 3.3. The effect of the seated person on C-rate.

3.4 Effect of C-rate on rate of heat generation in battery cell
As the C-rate increases, heat generation increases rapidly because of the large amount of current being drawn from the battery cell. The heat generation increases from 3.5 W to 10 W when the C-rate is increased from 0.75 to 5.5. The heat generation could be as high as 42.5 W which can be seen from Figure 3.4.

Figure 3.4. The effect of C-rate on heat generation in battery cells.

3.5 Effect of C-rate on battery cell temperature.
As the C-rate increases according to operating conditions, the battery cell temperature increases. It is seen from the result that the battery cell temperature could be as high as 80 °C for a time-lapse of 0.27 hours as the battery cell is discharged at 10 A current (5 C-rate). Battery cell temperature goes beyond
the 55 °C for 5 C-rate conditions which necessitates the battery thermal management system which limits the battery cell temperature below the 55 °C for better performance and safety of battery pack.

4. Effect of ambient temperature on battery cell terminal temperature
To understand the consequence of the environment on the rate of heat generation, ambient temperature is varied from 25 °C (winter) to 40 °C (summer) to evaluate the battery cell terminal temperature. The consequence of ambient temperature on the battery cell terminal temperature is shown in Figure 4 when a 5 A current is being drawn from the battery. It is seen from the result that the battery cell terminal temperature could be as high as 68 °C in winter and 84 °C in summer for a time-lapse of 0.55 hours.

Conclusion
It can be concluded from the above results that the efficiency and lifespan of the battery cells are susceptible to the vehicle's climatic conditions, battery conditions, and operational characteristics. For proper operation, the battery has to work in a strict state. It is vital to bound the battery cell temperature below 45-55 °C and the temperature difference between adjusting cells must not be increased over 5 °C. It is very essential to design and develop appropriate BTMS to increase efficiency and minimize the weight and size of EVs. BTMS is indeed not useful for extending the efficiency and life of a battery, but also from a protection perspective.

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