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# Thermal Modeling Of Lithium Ion Batteries For Temperature Rise Predictions In Hybrid Vehicle Application

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***Abstract* – In order to develop a hybrid vehicle with lithium ion battery packs, it is necessary to understand the thermal behaviour of the lithium ion batteries used. This paper focuses on predicting the temperature rise of lithium ion batteries during a drive cycle in hybrid two wheeler applications. To predict the rise in temperature, a model is developed in Simulink, parameterized using the empirical parameters. The model is based on the Joule heating effect and heat capacity equation while considering the variation of internal resistance with respect to ambient temperature of operation, state of charge and C rate of operation. The internal resistance is measured by parameter evaluation testing through the pulse power characterisation method. To validate the Simulink model, the lithium ion batteries are tested on standard drive cycles and constant current discharges, and the rise in temperature is measured. The accuracy of the Simulink model was found to be ± 2.2°C, which is acceptable for this study and comparable to the other available models in the literature.**

***Key words – Joule heating; internal resistance; hybrid pulse power Characterisation; State of charge; C rate.***

## I. INTRODUCTION

In everyday life, transport needs are often satisfied by automobiles. The main power source in a conventional automobile is an Internal Combustion (IC) engine, which heavily depend on fossil fuels. The fossil fuel consumption is increasing at a rapid rate, the total fossil fuel consumption has increased by more than three times in the past four decades [1] and if the fossil fuel consumption continues at the same rate it is predicted that oil, coal and gas will last only for the next 35, 107 and 37 years respectively [2]. Global warming is slowly increasing. A study by NASA reports that average global temperature has increased by 0.8°C since 1880, which is predominantly due to the entrapment of greenhouse gases in atmosphere [3]. A significant contributor to air pollution and greenhouse gases is the emission from the automobiles [4]. One of the more efficient solution for the problem of air pollution and fossil fuel consumption caused by conventional IC engines is the usage of battery operated vehicles [5], [6]. In the battery operated vehicles lithium ion batteries are the prevalent choice for energy storage [7], due to high energy density, high specific energy, high voltage, long life and low self-discharge [5], [8]. The performance of battery operated vehicles such as Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) depends on the performance of the battery packs, which in turn depends on the temperature range in which they are operated [9]. For better performance from lithium ion battery packs it is necessary to maintain the temperature of all the individual cells within the optimum range. To prolong the life and optimize the energy usage of a lithium ion battery, it is necessary to predict the thermal behaviour of the battery [10]. An accurate mathematical model for predicting the temperature dynamics is essential for the development of battery management systems.

## II. LITERATURE REVIEW

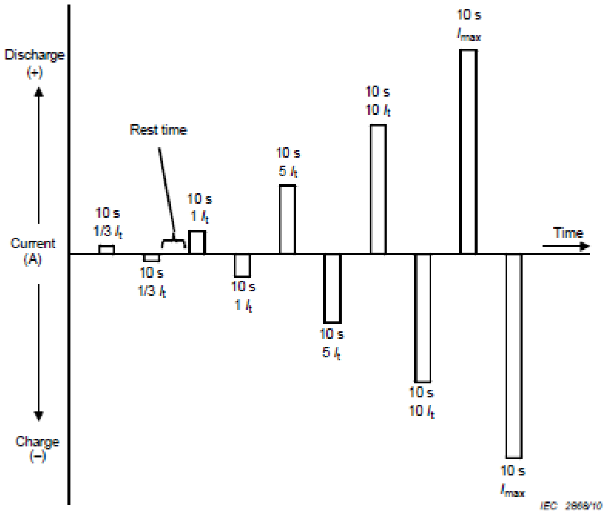
To develop a model for temperature rise prediction, a literature review was done focussing on two main areas. One is the causes for heat generation within a lithium ion battery pack and the other is different types of battery modelling techniques. From Zang’s work [11] and Sato’s work [12] it is understood that Joule heating, entropic effect and polarization effect are the major contributors of heat generation within a lithium ion battery. However from Srinivasan *et al.*’s work [13] and Jeon *et al.*’s work [8] it is clear that in high C rates of operation the Joule heating effect is dominant. In automobile applications the C rate of operation is often high due to varying acceleration from the vehicle, hence in this battery model for temperature rise prediction, only Joule heating is considered. The heat generated due to Joule heating effect is calculated by considering the total internal resistance, so that polarization heat is also taken into account. From the literature [14], [15], [16], [17] it is understood that the internal resistance in Joule heating effect calculation is not constant, it varies with respect to ambient temperature of operation, state of charge of the battery, C rate of operation and the direction of current. The variation of internal resistance with respect to ambient temperature and state of charge is clearly explained and quantified in literature [18]–[20], however variation with respect to C rate and direction of current flow is not well quantified in the literature. Hence after internal resistance measurement, the variation of internal resistance with respect to each variable is analysed and the variables which have considerable impact on internal resistance are taken into account. The internal resistance can be measured through Hybrid Pulse Power Characterization (HPPC) method [14], [15] and Electrochemical Impedance Spectroscopy (EIS) [7]. The HPPC method is widely used and Benger *et al.* [7] in their work have claimed that HPPC is more accurate than EIS. Hence it is decided that parameter evaluation testing for internal resistance measurement will be done by HPPC method. From the literature [7], [15], [21] it is understood that Simulink platform of Matlab is suitable for temperature rise prediction models. By analysing the models in the literature [9], [15], [18], [28], [29] it is understood that a model developed with an error of up to 2.5°C is accepted as an accurate model. The models in the literature considered heat generation due to the Joule heating and the entropy effects with more parametric input data and the models are computationally time consuming [18]. Hence it is decided to develop a model which is less complex and computationally fast.

## III. PARAMETER EVALUATION TESTING

HPPC testing is done in accordance to standard IEC-62660 [23]. The internal resistance varies with respect to ambient temperature of operation, state of charge (SOC), C rate and direction of current flow. Parameter evaluation testing for internal resistance is done at different ambient temperatures from 0°C to 55°C (operating temperature range considered for hybrid two wheeler application), the HPPC testing is done at six different ambient temperatures between 0°C and 55°C i.e. at 0°C, 11°C, 22°C, 33°C, 44°C and 55°C. At each temperature SOC of the battery is varied from 90% to 10% (operating SOC range for lithium ion batteries) in steps of 10% and parameter evaluation testing is done using five charge and discharge pulses at different C rate as per standard. The five pulses from the HPPC testing standard IEC-62660 are shown in Figure 1.

Figure 1 - Standard pulse from IEC-62660 [23]

However the same standard pulse with alternate discharge and charge cannot be used because the maximum charging current and discharging current are not equal in most of the lithium ion batteries. In order to keep the SOC of the battery at the same level, the standard pulse has to be modified. Therefore after each discharge pulse the amount of charge taken out from the cell is calculated in amp-secs and the charge pulses are modified in such way that the amount of charge supplied to the cell (in amp-secs) will be equal to the amount of discharge, the duration of the charge pulse is modified to account for the change in SOC. Sufficient rest is given between two consecutive charge pulses.



For each given input current pulse, the corresponding voltage response is measured and from the voltage response and current input the internal resistance is calculated. The internal resistance calculation is based on Ohms law.

After measurement the variation of internal resistance with respect to each parameter is analysed. It is found that variation of internal resistance with respect to ambient temperature of operation, SOC of the battery and C rate of operation are significant, whereas variation of internal resistance with respect to direction of current is negligible.

Figure 2 shows the variation on internal resistance at different SOC’s between 0°C and 55°C during 1C discharge. The internal resistance varies up to 79% between 0ºC and 55ºC; the maximum variation is at 20% SOC but even at other SOCs the variation is above 60%. Hence it is clear that variation of internal resistance with respect to ambient temperature of operation is significant.

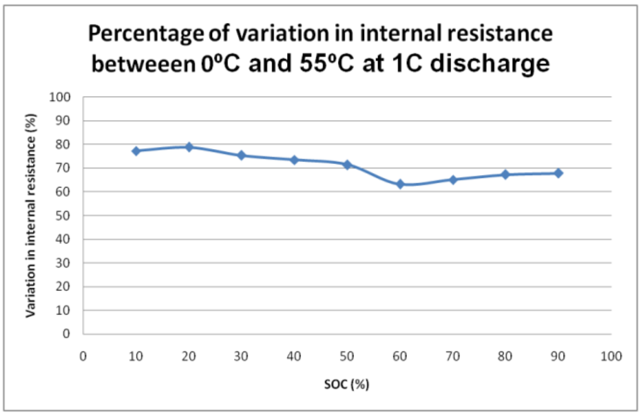


Figure 2 – Percentage of variation in internal resistance between 0ºC and 55ºC during 1C discharge at different SOC's

Figure 3 shows the variation of internal resistance at different SOCs between 1C and 10C discharge at the constant ambient temperature of 22ºC. Maximum variation in internal resistance with respect to C rate is 15% at 70% SOC.

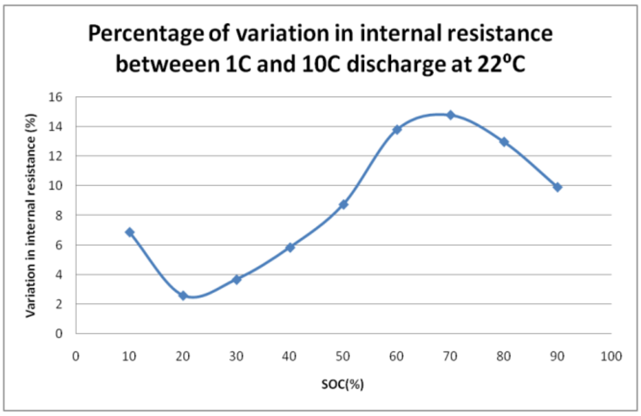


Figure 3 – Percentage of variation in internal resistance between 1C and 10C discharge at different SOC's at 22ºC

Figure 4 shows the variation of internal resistance during charging and discharging at different SOCs. The maximum variation is up to 5% which is at 90% SOC, at other SOC's variation of internal resistance with respect to charging and discharging is less than 3%, which is negligible.

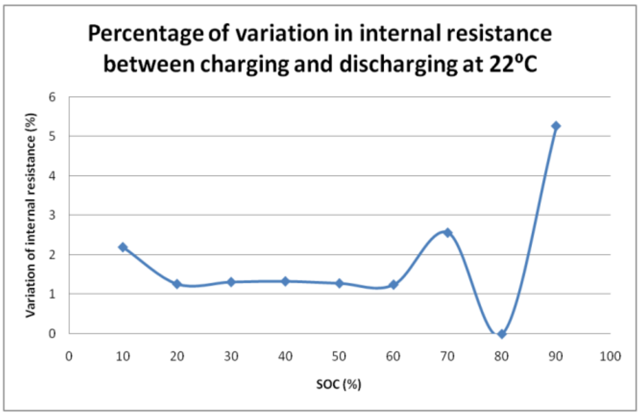


Figure 4 – Percentage of variation in internal resistance between charging and discharging at different SOC's at 22ºC

Therefore in the Simulink model variation of internal resistance with respect to ambient temperature, SOC and C rate are considered and the effect of direction of current flow is neglected.

## IV. MODELLING

The aim of the model is to predict the rise in temperature with the drive cycle input. The model is developed in the Simulink platform of Matlab and it is based on the concept of Joule heating effect and heat capacity equation. The model is based on the assumption that Joules heating is the major contributor for heat generation in automobile application and the effect of entropy is negligible at higher C rates.

The heat generated is calculated using the Joule heating effect as follows:

$$Q= I^2R \qquad (1)$$

Where

Q – Heat generated (Watts), I – Current (Amps) and R – Internal resistance (Ohms).

The current value is taken from the drive cycle input for every time step. The internal resistance is calculated from the parameter evaluation test, which is stored in the form of a look-up table in the Simulink model. Since the internal resistance value varies with respect to three variables SOC, ambient temperature and C rate of operation respectively, it is stored as a 3D lookup table in Simulink. From these values heat generated is calculated using the Joules heating effect. The heat generated is in Watts, i.e. Joules per second. In order to find the amount of heat energy in Joules, the heat generated from the Joule heating effect equation is multiplied by the size of the time step. Then the heat energy in Joules is equated against the heat capacity as shown in equation 2.

$$Q = mC_p\Delta T \qquad (2)$$

where

Q – Heat energy (Joules), m – Mass of the battery (Kg), $C_p$– Specific heat capacity of the battery (J/Kg°C) and ΔT – Rise in temperature (°C)

The mass of the battery is known from the battery specification sheet and the value of specific heat capacity is measured using a calorimeter. From this equation, the rise in temperature is calculated for a single time step.

The inputs to the Simulink model are the time and current data from the drive cycle, the capacity of the battery in amp-hrs, the initial SOC of the battery, ambient temperature of operation, mass of the battery and specific heat capacity of the battery.

Based on the input conditions the Simulink model calculates the SOC and C rate for each drive cycle time step, interpolates the corresponding internal resistance and calculates the heat generated. The model updates the input conditions for each time step and interpolates the corresponding value of internal resistance. The heat generated is equated in heat capacity equation and the rise in temperature for a single time step is found. The summation of rise in temperature gives cumulative rise in temperature at the end of drive cycle.

The model also considers the effect of cooling. The empirical data from the drive cycle testing is used for cooling rate calculation. After the drive cycle is completed, the temperature is measured for the next 60 minutes for the cooling rate calculation, because from the temperature measurement it is observed that major amount of cooling takes within 60 minutes after completion of the drive cycle. The fall in temperature is plotted against the time and the cooling curve is obtained, the cooling rate is based on Newton's law of cooling [24] which is as follows:

$$T(t) = T_s + (T_0 - T_s)\, e^{(-kt)} \qquad (3)$$

where

T(t) -Temperature of an object at a certain time (°C), t -Time (seconds), $T_s$-Temperature of the surroundings (°C), $T_0$-Starting temperature of the object (°C) and k - Cooling constant (1/second)

The cooling constant (k) is calculated from the curve for three cells at six different temperatures. The average cooling rate is used in the model. The average cooling rate is subtracted from the rise in temperature in each step and then the values are added up to give the cumulative rise in temperature. The block diagram of Simulink model is shown in Figure 5.

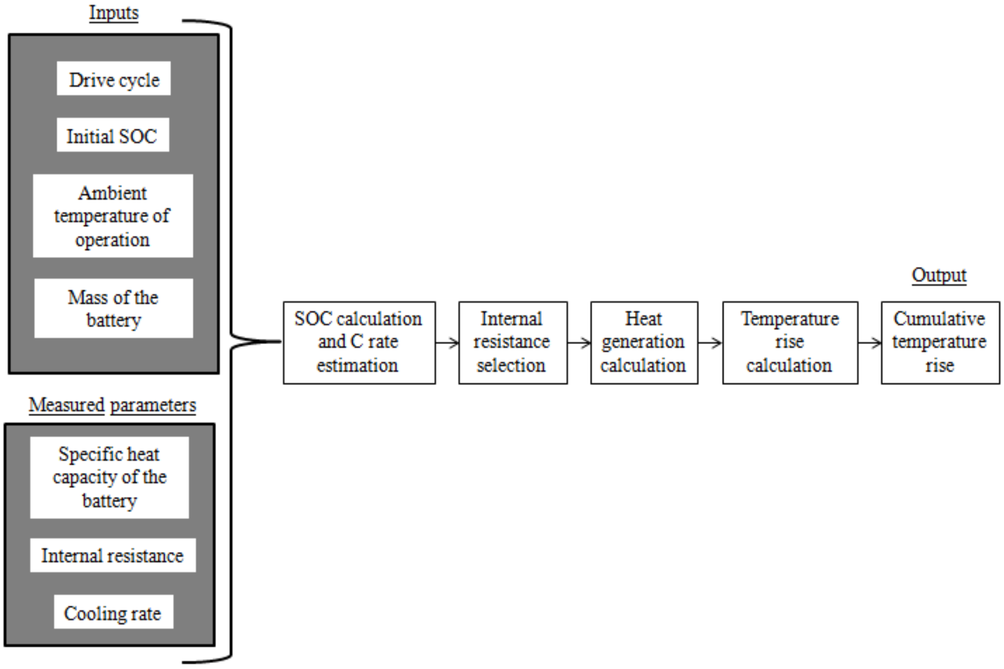


Figure 5 – Block diagram of Simulink model to predict the rise in temperature

## V. MODEL VALIDATION

To validate the Simulink model the cells are tested on the drive the cycles and the rise in temperature is measured. The drive cycle testing is done inside a thermal chamber to maintain the constant temperature at different ambient conditions. The cells are kept inside the insulation box made up of polystyrene which is placed inside the thermal chamber. The polystyrene box provides good insulation to the cells to prevent the cells from direct contact with the air which is moving inside the chamber to maintain the ambient temperature of the chamber. This is done in order to prevent the cooling of the cells due to air flow. The test setup is shown in Figure 6.

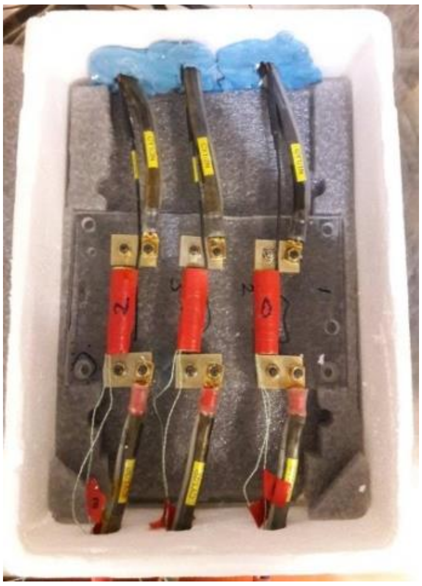


Figure 6 – Lithium ion cells placed inside polystyrene box for testing

The rise in temperature is measured on three different cells and the average value of rise in temperature is considered for the purpose of model validation. The rise in temperature is measured for two drive cycles and two constant current discharge tests.

The same initial conditions of SOC and ambient temperature of operation at which the testing is done are given as inputs to the Simulink model and the rise in temperature is predicted. The predicted values are compared against the actual measured values.

Drive cycle 1 and 2 are validated at six different ambient temperatures between 0°C and 52°C. Table 1 and 2 gives the comparison between the measured rise in temperature and the simulated value from the model.

Table 1 - Comparison between the measured data and the simulation results for the Drive cycle 1

| Ambient temperature of operation (°C) | Measured rise in temperature (°C) | Simulated rise in temperature (°C) | Difference between simulation and measurement (°C) |
|---|---|---|---|
| 0 | 16.80 | 17.53 | 0.73 |
| 15 | 12.61 | 12.15 | -0.46 |
| 25 | 10.02 | 9.99 | -0.03 |
| 35 | 8.67 | 8.87 | 0.20 |
| 45 | 7.23 | 8.21 | 0.98 |
| 52 | 7.41 | 7.82 | 0.41 |

The accuracy of the Simulink model for the drive cycle test 1 is within ± 1°C.

Table 2 - Comparison between the measured data and the simulation results for the Drive cycle 2

| Ambient temperature of operation (°C) | Measured rise in temperature (°C) | Simulated rise in temperature (°C) | Difference between simulation and measurement (°C) |
|---|---|---|---|
| 0 | 20.26 | 20.72 | 0.46 |
| 15 | 13.87 | 14.87 | 1.00 |
| 25 | 11.47 | 12.82 | 1.35 |
| 35 | 9.58 | 11.55 | 1.97 |
| 45 | 8.75 | 10.73 | 1.98 |
| 52 | 8.02 | 10.26 | 2.24 |

The accuracy of the Simulink model for the drive cycle test 2 is within ± 2.2°C.

Constant current discharge test 1 is done at two different ambient temperatures and constant current discharge test 2 is done at four different ambient temperatures. The comparison between the measured data and the simulation is shown in Table 3 and 4 respectively.

Table 3 - Comparison between the measured data and the simulation results for Constant current discharge test 1

| Ambient temperature of operation (°C) | Measured rise in temperature (°C) | Simulated rise in temperature (°C) | Difference between simulation and measurement (°C) |
|---|---|---|---|
| 0 | 47.01 | 48.81 | 1.80 |
| 15 | 39.40 | 41.54 | 2.14 |

The accuracy of the Simulink model for constant current discharge test 1 is ± 2.1°C.

Table 4 - Comparison between the measured data and the simulation results for Constant current discharge test 2

| Ambient temperature of operation (°C) | Measured rise in temperature (°C) | Simulated rise in temperature (°C) | Difference between simulation and measurement (°C) |
|---|---|---|---|
| 0 | 21.89 | 22.51 | 0.62 |
| 15 | 15.79 | 16.59 | 0.80 |
| 25 | 12.75 | 14.45 | 1.60 |
| 45 | 10.31 | 12.00 | 1.69 |

The accuracy of the Simulink model for constant current discharge test 2 is ± 1.7°C.

The accuracy of the Simulink model is ± 2.2°C for all the validations tests done. In most of the thermal models discussed in the literature, the heat generation due to both the Joule heating and entropy effects are considered making the model more complex with more measured data. Accuracy of the models mentioned in the literature varies up to ± 2.5°C. The model developed here is made simple with less measured data and the actual cooling rate measured from the cells is taken into account.

## VI. CONCLUSION

The Simulink model is validated for the drive cycles and the constant current discharge tests and it is predicting the rise in temperature with acceptable accuracy of ± 2.2°C. The developed model is comparatively less complex, computationally fast and of comparable accuracy with the best models available in the literature. All the parameters used in the heat generation calculations and temperature rise predictions are measured directly from the battery, none of the parameters are approximated or taken from the literature.

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