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DERIVING INSTANTANEOUS ELECTRO-THERMAL PARAMETERS AND HEAT GENERATION FROM CONSTANT-CURRENT DISCHARGE DATA

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ABSTRACT

Early-stage Battery Thermal Management System (BTMS) design can be constrained by limited manufacturer data, resulting in the use of steady-state thermal assumptions. An analytical methodology is introduced to extract the real-time cell resistance, instantaneous efficiency, and transient heat generation directly from standard constant-current discharge curves, and Open Circuit Voltage (OCV) profiles. By evaluating the time-dependent voltage differential against current, equivalent cell resistance and transient heat generation are computed without explicit ohmic measurement or calorimetric testing. This enables direct, real-time coupling of electrical and thermal models. Application to an NMC chemistry cell demonstrates concentration losses dominate below a 20% State-of-Charge (SOC), increasing transient heat generation, and decreasing instantaneous efficiency. Extracting the time-dependent electro-thermal parameters provides the required quantitative inputs for benchmarking cells & accurately sizing BTMS cooling capacities.

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1. INTRODUCTION

Battery manufacturers typically provide limited operational data on their cells, consisting primarily of constant-current discharge curves (C-rates), nominal voltage limits, maximum voltage, minimum voltage, maximum charging current, maximum discharging current, and a single static value for internal impedance. This cell data is sufficient to build a preliminary electrical equivalent model but does not provide enough information to develop and model Battery Thermal Management Systems (BTMS).

To accurately design a battery pack, electrical and thermal model cannot be treated as isolated systems. A battery is a time-dependent electromechanical system, whose internal resistance and efficiency are highly dependent on its transient state-of-charge (SOC) and operating temperature. Because temperature gradients across a battery pack directly dictate charge/discharge limits, the model must be inherently coupled. However, the exact transient heat generation as a function of current and SOC is a parameter that is universally omitted from standard manufacturer data sheets.
A sample of the cell discharge curve is shown in Figure 1.

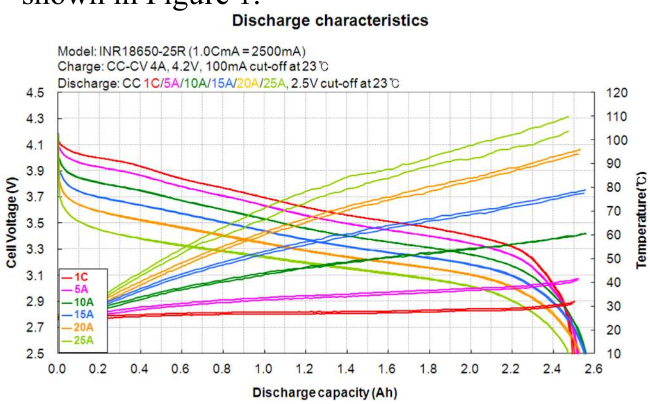

Figure 1- Sample Battery Discharge at Constant Current [1]

As the C-rate increases, the temperature of the cell also increases, and this increase is not negligible. In the case of the 25 A the cell begins at 25 °C and at the completion of discharge, is over 100 °C. The high cell temperatures will reduce battery life and increase the risk of thermal runaway. Note the cell manufacturer does provide data on the heat generation of the cell; they will provide an Ohmic resistance but no distinct heat generation at a function of current and state of charge. This piece of information is missing from the manufacturer. The cell heat is not measured at the cell level; however, it can be estimated through Joule heating as shown in Equation (1).

$$\dot{Q} = I^2 R \tag{1}$$

It is unknown how cell resistance changes with state of charge and C-Rate. It is also unknown how the heat generation changes with state of charge.

A battery, like a fuel cell, is an electro-chemical system which converts electrochemical energy into electricity and heat. Like any thermodynamic processes there are losses; typically, losses show themselves as light, heat and/or sound.

The heat generation of any processes or components needs to be determined to maintain operation within the desired temperature range. If the temperature is range is exceeded there will be reduced performance and reduced life. It is acceptable to over cool an engine as it can compensate via the thermostat. On the other hand, batteries must be kept in the desired temperature range. This means if the batteries are too cold, they must be heated and if they are too hot, they must be cooled. This is the primary reason why the heat generation of the battery must be known.

The cell heat generation will impact the sizing of the cold plate; the cold plate must be sized to remove enough heat to prevent the cells from going over temperature. The other parameter related to cold plates is the coolant flow. The goal of the coolant flow is to keep the coldest and warmest cell within 5 °C of one another. The heat generation needs to be known to compute the minimum coolant flow required to maintain the 5 °C temperature difference between the coldest and warmest cell.

Table 1: Types of Battery/Cell Models [2]

Model Nature			Model	Data	Physical Interpretability	Analogy	Accuracy	Complexity	Suited Application
Electro-chemical			Pure Electro-Chemical	P	H	White box	VH	H	Battery design
			ECM/Reduced order Electro-Chemical	SE	M	Grey box	H	M	
Electrical	Analytical		Peukert's model	E	L	Black box	M	M	Prediction
			Rakhmatov and Vrudhula	SE	M		M	M	
			Sheperd other iterations	SE	M		M	M	
			State-Space	E	L		M	M	
	ECM	Simples	Simple Rint	E	M	Grey box	L	L	Real time control, SoC estimation, ...
			Enhanced Rint	SE	M		L	L	
			RC	SE	M		L	L	
		Thevenin	1st order	SE	M		L–H	L–H	
			2nd order	SE	M				
			3rd order	SE	M				
			nth order	SE	M				
		PNGV	1st order	SE	M		L–H	L–H	
			2nd order	SE	M				
			nth order	SE	M				
			Noshin	SE	M		M	M	
			Neural nets	E	L		H	H	
	Impedance		Frequency domain	SE	L–M	Grey box	M	M	Characterization and real time operation
Thermal			Analytical Thermal	P–SE	H	White box	H	H	Real time
			ECM Thermal	SE	M	Grey box	M	M	
Mechanical/Fatigue			Fatigue/Mechanical	P–SE	H	Grey box		H	Design
Abstract model			Artificial Intelligence	E	L	Black box	M	M	Offline analysis
Combined models			Electro-Thermal	SE	M	Grey box	L–H	M	Real time
			Thermo-electrochemical	P	H			H	
			Thermo-Mechanical	SE	H			H	

* E: Empirical, H: High, L: Low, M: Medium, P: Physical, SE: Semi-Empirical, VH: Very High.

The thermal system is impacted by the battery heat generation of the cell. The Air Condition (AC) compressor must have enough refrigeration capacity to keep the cells in their optimum temperature range. The compressor must have sufficient Coefficient of Performance (COP) to support the cooling and heating of the battery. If the heat generation is understood too late the cells will be thermal limited and it will be rendered less effective, and it will also reduce the battery life. This is why the heat generation must be known at the cell level and during the initial design of the battery pack. A lack of understanding of the heat generation at the cell level will lead to additional costs in redesigning and/or an oversized cooling system which will add additional weight to the application.

2. Theory

The first step toward understanding the cell is to understand the relationship between Open Circuit Voltage (OCV) and discharge voltage and what can be derived from this relationship. Table 1 shows all the cell models used for understanding how the cell will perform in an electric circuit.

Each model has a different equivalent circuit. These models work electrically but they do not support thermal. The thermal model requires combined models; there is not one model that resolves the electrical system and thermal systems. It is possible to obtain heat generation with the state of charge of the battery, the discharge voltage and the current.

Figure 2 shows a simple battery model when the open circuit voltage is constant, and internal resistance is a function of the state of charge.

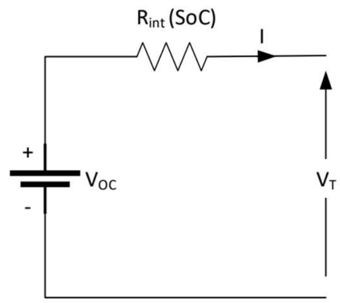

Figure 2 – Simple Battery Model [2]

One of the issues with a simple cell model is that the assumed open circuit voltage does not change with the state of charge, but in fact the open circuit voltage is a function of the state of charge. This model acknowledges the cell resistance is changing with state of charge which will impact the discharge voltage. Another equivalent circuit model approximates the cell with capacitors and resistors as shown in Figure 3.

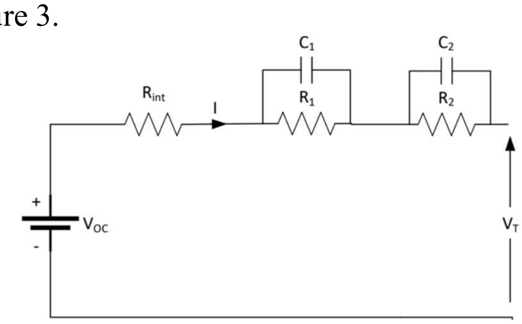

Figure 3 Second Order Thevenin [2]

As in the other model, the open circuit voltage is constant. Capacitors and resistors are used to better predict transient behavior. These models only look at the electrical characteristics and not the thermal. As shown in Table 1 the electrical model needs to be coupled with the thermal model.

To compute heat generation, both the current and the resistance need to be known. In the case of the simplified cell model, cell resistance is a function of state of charge. The resistance of the cell must be known to compute the heat generation of the cell.

Whilst the fundamental formulation of battery resistance to couple thermal & electrochemical models has been well documented in battery related literature for a relatively long time, acquiring accurate, dynamic resistance data often requires long drawn & expensive testing. To address this gap, this paper demonstrates a methodology to calculate time-dependent heat generation, cell resistance, and efficiency directly from standard discharge curves, without requiring explicit priori Ohmic measurements.

There are some limitations on the Joule heating. One limitation is no chemical reactions can be present. In the cell, however, there is an oxidation and reduction reaction. The proposed method to calculate cell heat generation will bypass Joule heating and calculate the heat generation without knowing the cell resistance. In fact, the proposed method will calculate resistance which can also be used to compute the heat generation via the Joule heating formula.

A sample cell discharge curve is shown in Figure 1. Joule heating does have some assumptions associated with it; the first assumption consists of following Ohms Law. The second assumption consists of uniform material properties, and the third assumption states the system needs to be in steady state.

In the case of a battery, the system cannot be in steady state because either the voltage or current are changing with the state of charge, and the resistance is dependent on the state of charge of the battery. With the resistance of the battery continuously changing what value of resistance should be used to calculate heat generation?

There are several battery models as shown in Table 1. There is not a one-size that fits all models in the battery world. The cell performance depends its SOC and its temperature and thus the electrical and thermal system must be modeled together. While standard equivalent circuit models use resistors, and capacitors to approximate electrical characteristics, they cannot resolve thermal behavior independently. Using a combined electro-thermal model to calculate heat generation saves computational time and simplifies the battery pack development process.

The first step is to examine the battery cell discharge curve and to understand the drop in discharge voltage. In the electrical world Ohm's law assumes a linear relationship between voltage and current. In Figure 1, some of the losses are linear and there are nonlinear losses in a cell; this implies Ohm's law is valid on a portion of the battery discharge curve, but Ohm's Law can be used to gain additional insight at each data point.

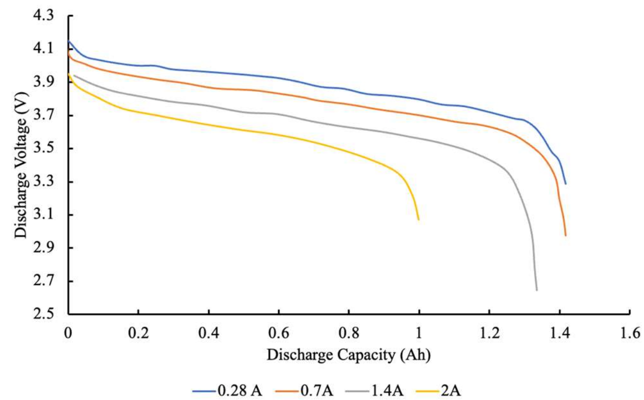

Figure 4 Sample Cell Discharge Curve [3]

There is a region of the discharge curve where the discharge voltage varies linearly with capacity and there are regions where the discharge voltage varies non-linearly with cell capacity. There are three regions of losses in the cell, the first region is the activation loss region, the second region is the Ohmic loss region, and the third region is the concentration loss region. The activation and concentration losses are non-linear losses. If the cell is operated in the Ohmic losses region then the cell will fully follow Ohms's Law. The equilibrium voltage of a cell is based on the Gibbs free energies, as shown in Equation 2.

$$E^o = \frac{-\Delta g_{rxn}}{nF} \qquad (2)$$

The change in Gibbs free energy is the starting point of any electrochemical reaction where the maximum theoretical equilibrium voltage can be derived. It is important to note that the open circuit voltage (OCV) and equilibrium voltage are distinct properties. They are typically only equal near the voltage plateau in the voltage versus capacity curve. At all other points, one cannot directly derive the OCV with the true equilibrium voltage. From the Open Circuit Voltage, discharge voltage is the result of subtracting all the losses from the cell as shown in Figure 5. The difference in voltage leads to the losses in the cell.

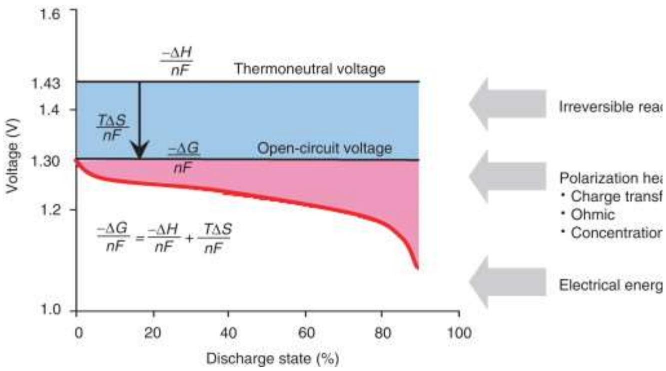

Figure 5- From Open Circuit Voltage to Discharge Voltage [4]

The Open Circuit Voltage (OCV) depends on the chemistry of the anode and the cathode. In cells the OCV will also depend on the state of charge as shown in Figure 6.

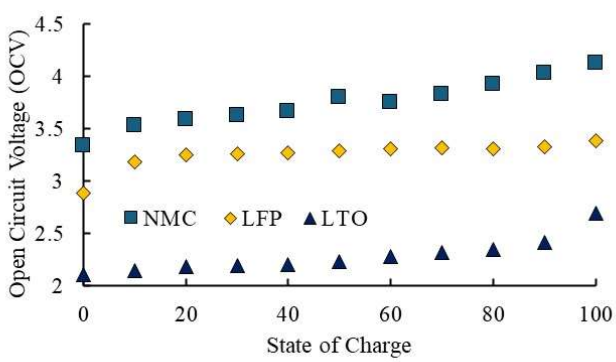

Figure 6- Sample Open Circuit Voltage [5]Error! Reference source not found.

Different lithium-ion cell chemistries do have different Open Circuit Voltage (OCV) relationships to state of charge as shown in Figure 6. LFP and LTO chemistries tend to have a constant OCV profile while NMC chemistry does show a voltage change from 3.3 V to 4.12 V. This is the reason why cell chemistry must be known. This also confirms the OCV is changing with the state of charge of the cell. According to Figure 6, there are three types of cell losses, and the losses are charge transfer losses, Ohmic losses and concentration-based losses. The other name for charge transfer losses are activation losses. The difference between the open circuit voltage and discharge voltage is shown in Equation 3.

$$E_D = E^o(q) - \frac{R_u T}{\propto nF}\ln\left(\frac{j}{j_o}\right) - rj - \frac{R_u T}{nF}\ln(1 - \frac{j}{j_l}) \quad (3)$$

The first term is the open circuit voltage of the cell, and this term is a function of cell temperature and the state of charge of the cell. The second term is the activation losses, third term is the Ohmic losses, and the last term is the concentration losses. The activation and concentration-based losses are non-linear losses of the battery.

The reported Ohmic resistance may not capture the activation losses and the concentration losses but there is a way to capture all the losses of the battery, and this is done by rearranging Equation 3 moving the open circuit voltage to the other side of the Equation as shown in Equation 4.

$$E_D - E^o(q) = -\frac{R_u T}{\propto nF}\ln\left(\frac{j}{j_o}\right) - rj - \frac{R_u T}{nF}\ln(1 - \frac{j}{j_l}) \quad (4)$$

The voltage difference can be multiplied by negative one and equation 5 is obtained

$$E^o(q) - E_D = \frac{R_u T}{\propto nF}\ln\left(\frac{j}{j_o}\right) + rj + \frac{R_u T}{nF}\ln\left(1 - \frac{j}{j_l}\right) \quad (5)$$

The difference in the voltage is the summation of all the losses of the battery. If the current is known, the heat generation can be computed by multiplying by the current as shown in Equation 6.

$$(E^o(q) - E_D)j = \left(\frac{R_u T}{\propto nF}\ln\left(\frac{j}{j_o}\right) + rj + \frac{R_u T}{nF}\ln\left(1 - \frac{j}{j_l}\right)\right)j \quad (6)$$

Currently there are two efficiencies being used for cells, namely the Columbic and Voltage efficiencies. These efficiencies are not an instantaneous efficiency; they do not consider what is going on in real time. An instantaneous efficiency needs to be considered when the cells are charging and discharging. A process is needed to compute instantaneous efficiency to better model and understand cells.

The activation, Ohmic and concentration losses all reduce the open circuit voltage and as a result an efficiency can be computed by taking the output power by the input power as shown in equation 7.

$$\eta = \frac{E_{Discharge}}{E^{O}(q)} \tag{7}$$

With the proposed cell efficiency, it can now relate the open circuit voltage to the discharge voltage real time. Cell efficiency will depend on the state of charge of the chemistry, state of charge and cell losses. The cell efficiency needs to be reviewed to see how it changes over the operating range of the cell. The cell efficiency can be data mined from the cell discharge curves.

If Equation 8 is rearranged to solve for the discharge voltage and it is substituted into Equation 7, the heat generation can be related to via the efficiency as shown in equation 8.

$$E^{o}(q)(1-\eta)j = \left(\frac{RT}{\propto nF}\ln\left(\frac{j}{j_o}\right) + rj + \frac{RT}{nF}\ln\left(1 - \frac{j}{j_l}\right)\right)j \tag{8}$$

The proposed approach allows for the discharge voltage and heat generation to be coupled together. This will allow for the coupling of the electrical and thermal models. Another approach can be used to yield the same result. Joule heating is a relationship between current and resistance to obtain heat generation as shown in equation 1.

The cell discharge data, state of charge, and the open circuit voltage can be used to determine the heat generation, cell efficiency and cell resistance. The heat generation, cell efficiency and resistance are data mined from the cell discharge curve. Resistance of the cell can be computed by taking advantage of Ohms Law as shown in Equation 9.

$$\frac{\Delta E}{I} = R \tag{9}$$

If the change in voltage is the difference between OCV and discharge voltage, then it can be substituted into equation 9 to yield equation 10.

$$\frac{E^{O} - E_{Dis}}{I} = R \tag{10}$$

If equation 10 is substituted into equation 1 then equation 11 is obtained.

$$\left(\frac{E^{O} - E_{Dis}}{I}\right) I^2 = (E^{O} - E_{Dis})I \tag{11}$$

Both methods yield the same results, but the proposed method bypasses the need for knowing the electrical resistance. The only parameters needed are the state of charge, open circuit voltage and the discharge voltage.

One of the simple battery models is shown in Figure 2, and in this case the cell resistance is changing along with the state of charge. The proposed method determines cell resistance at each data point.

As stated earlier, the heat generation at the cell level is an important parameter for battery performance, battery life, and cooling system sizing. It is required to design a battery pack and to size a thermal system, and to maximize cell life. The cell heat generation is not directly measured in cell testing but can be indirectly measured at the pack level through the temperature rise of the coolant across the pack along with the mass flow rate. If the predicted heat generation at the cell level is too low, then it will be too late to fix at the pack or module level. Additionally, if the predicted heat generation at the cell level is too high then the cooling system will be oversized and not very efficient. The existing cell data can be used to compute the heat generation at the cell level, and with the cell heat known it can be applied to the pack level to properly size the cold plate along with the thermal management system. The heat generation is measured without the determination of cell resistance.

If the cell heat generation is properly computed, then it can be easily computed at the module and pack level, and it will make it possible to maintain the cells in their proper temperature range and allow the thermal system to be sized properly.

The approach could also be used to compute heat generation real time and have the cooling system adjust accordingly. The proposed technique can be used to maximize cell space, optimally size the cooling system and reduce the risk of thermal runaway. The approach takes advantage of thermodynamics and the loss mechanisms of the cell. The next step is to examine the results extracted from the discharge curve.

3. Results

The first step is to obtain the chemistry of the cell to obtain the OCV and state of charge curve, since the discharge voltage and the state of charge are known. The battery used in Figure 1 is Nickel Manganese Cobalt (NMC) and its OCV is shown in Figure 7.

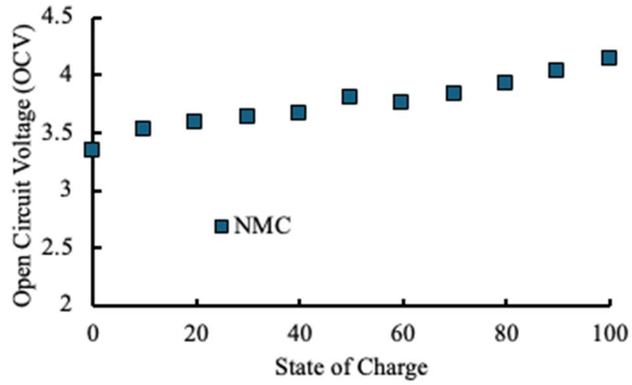

Figure 7- Open Circuit Voltage of NMC battery [5]

The open circuit voltage is a result of cell chemistry. The state of charge will impact the open circuit voltage. If the state of charge is known, then the open circuit voltage can be obtained. The cell tested in Figure 1 is an NMC Chemistry. The OCV in Figure 7 along with the discharge voltage from Figure 1 will be used to compute cell resistance, cell heat generation and cell efficiency.

With the OCV known, the difference between OCV and discharge voltage can be computed, and the cell resistance can also be calculated with equation 10. The cell resistance is shown in Figure 8.

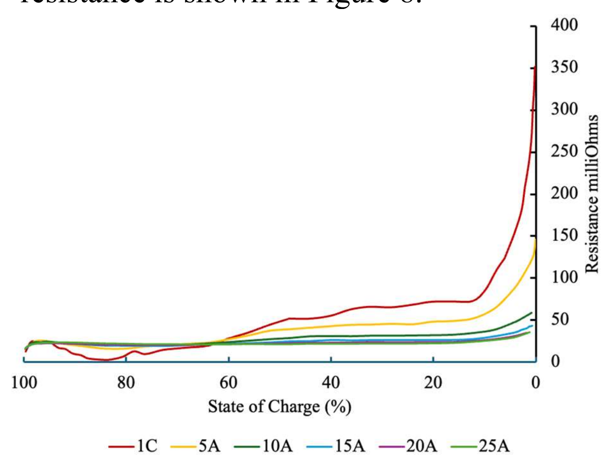

Figure 8- Computed Cell Resistance [1]

Computed cell resistance is not pure Ohmic resistance, it does however, contain the activation, Ohmic losses and concentration losses. If the voltage losses need to be isolated further, then more analysis of the resistance can be completed. All the cell losses will turn into heat and from a thermal point of view these losses will be sufficient for developing the thermal system.

Cell resistance can be used to compute the heat generated by the cell by using Joule heating equation as shown in Figure 1. The cell resistance does increase when the SOC is less than or equal to 20% and the resistance is linear when between 20-80%. When the SOC is greater than or equal to 80% the activation losses will dominate, but when the state of charge is 20% or less the concentration-based losses will be dominant. The resistance is dependent on the state of charge and the discharge current of the cell.

In the case of a battery only power system like a battery electric vehicle, operation will be from 100% SOC to minimum cell voltage, so rapid changes in the resistance must be accounted for. In cases of a hybrid vehicle, either an internal combustion engine or fuel cell, the state of charge of the battery can be controlled and the battery can be held in the 80% - 20% SOC range, and this can minimize cell heat generation. In cases where the system is a hybrid system that state of charge of the battery can be controlled and the battery can be kept out of the high resistance zone. If the battery is the only source of power, then the cooling system needs to be able to support this higher heat load.

The second piece of information obtained is the power discharge of the battery. By taking the discharge voltage and multiplying it by the current, the power discharge of the battery can be obtained as shown in Figure 9.

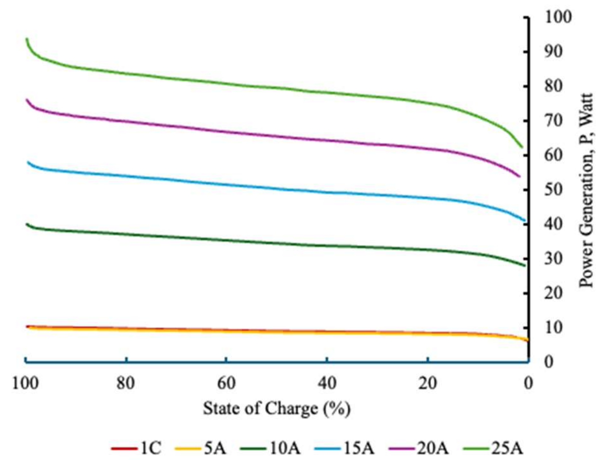

Figure 9- Computed Discharge Power of the Cell [1]

Under a constant current discharge, the power does not remain constant, instead it is decreasing as the state of charge decreases. The power output of the cell is dependent on the SOC of the cell and the discharge current. As the state of charge decreases, the discharge voltages decrease which will also reduce the power. At lower levels of charge, concentration losses increase, and this drives up the cell resistance and thus reduces the output power. The power discharge is stable between 20% and 80% SOC. The cell should be kept in this stable region.

The next piece of data which is extracted is the heat generation. This is done by using equation 11. The heat generation is shown in Figure 10.

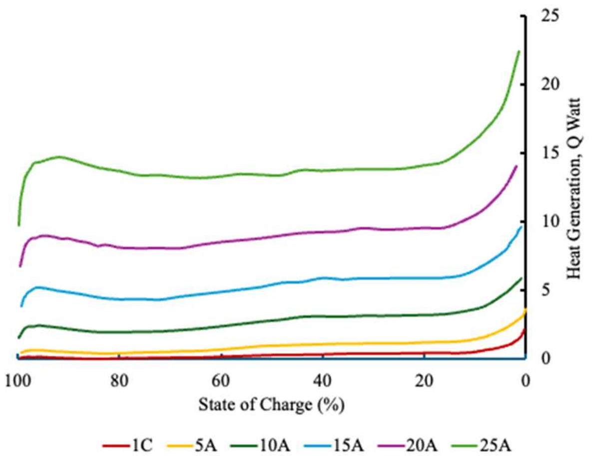

Figure 10- Computed Heat Generation of the Cell [1]

The heat generation does follow the same trend as the resistance. As the resistance increases so does the heat generation. The heat generation does increase when the state of charge is below 20%. This increased heat generation could lead to thermal runaway if the cooling system is not sized properly. In the case of a hybrid, the battery can be kept out of low state of charge zone by controlling the state of charge of the cell with the other power source.

The last piece of information gained from the analysis of the discharge curves is cell efficiency. The efficiency is obtained by dividing the discharge voltage by the open circuit voltage as shown in equation 7. The real time cell efficiency is shown in Figure 11.

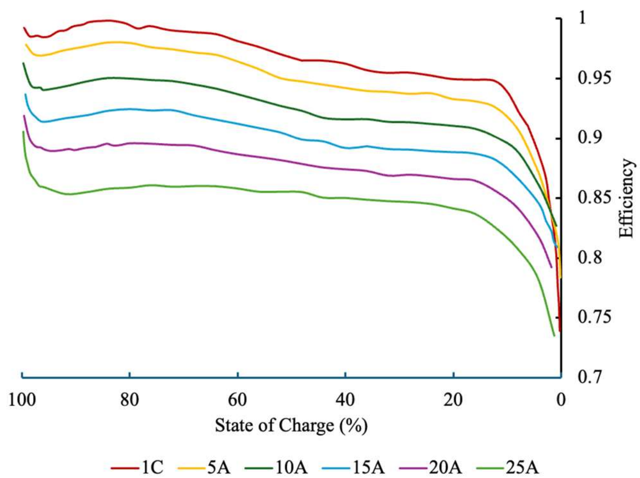

Figure 11- Computed Real Time Efficiency [1]

Based on cell resistance and heat generation, the cell efficiency drops dramatically when the state of charge is less than 20% SOC, and the efficiency stabilizes below 80% SOC. The cell efficiency depends on the state of charge and the discharge current. The cell efficiency will impact the power delivered by the battery. In instances where efficiency is decreasing the cell will have to deliver more power. In cases like battery electric vehicles, the efficiency will be changing real time adding a level of complexity to the system modeling, but in the case of hybrids the cell efficiency can be held constant by controlling the state of charge.

The cell efficiency based on the combination of Columbic and Voltaic efficiency stated to be approximately 92%. The real time efficiency does show this efficiency can be achieved at low current, but as current increases the cell efficiency decreases. This will have an impact on the amount of power the cell needs to produce to maintain performance.

The calculated resistances, power, heat generation and efficiency allow for a cell-to-cell comparison. The data mining shown allows for determination of information that can be used to size the thermal system and the cold plate of the battery pack and other design consideration.

4. Discussion

Cell resistance, cell efficiency, power output and heat generation can now be computed at each data point of a cell if the discharge voltage, the state of charge and the open circuit voltage are known. The cell resistance, cell efficiency and the heat generation are all extracted from the cell discharge curve. The new data allows for cells to be compared to one another. Resistance, efficiencies and heat generation can now be compared to seeing which cell meets the needs better. Resistance, efficiency and heat generation depend on the state of charge and the current discharge of the cell. There is not a need to fully rely on the cell manufacturer data. The key parameters can be obtained from the battery discharge curve.

The properties of the cell do not drastically change between the range of 80%-20% SOC. If the battery is the only source of power like in a battery electric vehicle, then the system needs to be designed from 100% SOC down to the minimum cell voltage and this would yield higher heat generation due to operation at lower state of charge causing potential thermal runaway along with an oversized cooling system. If the system is a hybrid, the state of charge of the cell can be controlled via the other power source, and as a result the heat generation of the cell can be minimized, and the cooling system capacity does not need to be as substantial.

The real time heat generation can be used to size the cold plate and determine the coolant flow required to meet the maximum and minimum cell temperature. The heat generation could also be calculated real time based on knowing the state of charge, open circuit voltage, discharge voltage and current. The better understanding of heat generation will reduce the risk thermal runaway.

The data can now be used to model the electrical and thermal together and determine how the thermal system will impact battery performance.

5. Conclusion

With the highly practical analytical methodology presented, to extract real-time cell resistance, instantaneous efficiency, and transient heat generation directly from standard constant current discharge curves, and Open Circuit Voltage (OCV) profiles. By calculating the time-dependent voltage differential across current, this approach bypasses the limitations of the steady-state Joule heating assumption, and the need for explicit *priori* ohmic measurements. The extracted parameters enable the direct, time-dependent coupling of electrical and thermal system models, which is a necessity for accurate, early-state Battery Thermal Management System (BTMS) design.

Application of this method to an NMC chemistry cell demonstrated that internal resistance and heat generation are highly dependent on transient State-of-Charge (SOC). Specifically, concentration losses dominate when SOC falls below 20%, resulting in a measurable increase in transient heat generation, and consequently, a decrease in instantaneous efficiency. Modeling these nonlinear thermal limits allows for certain insights: in Battery Electric Vehicles (BEVs), where full-depth discharges are standard, the BTMS cooling capacities must be explicitly oversized to handle low-SOC heat spikes to prevent thermal runaway. Alternatively, in

Hybrid Electric Vehicles (HEVs), control strategies can restrict operation to the highly efficient 20% -80% SOC window, minimizing the required refrigeration capacity. This methodology provides quantitative inputs required to benchmark cell chemistries, optimize cold plate dimensions, and accurate spec coolant flow rates.

Currently, the computed results presented in this work have not yet been compared to experimental test data for differing cells. For future work, whilst this analytical approach establishes a coupled lumped parameter electro-thermal base, questions remain regarding the localized thermal gradients within the cell structure itself. Therefore, future work should focus on validating these theoretical values against experimental data. This will include an empirical verification of the time-dependent heat generation using isothermal calorimetry to quantify the accuracy of the extracted parameters. Additionally, integrating these extracted time-dependent parameters into 3D multi-physics models would allow for characterization of anisotropic thermal conductivity, and localized hotspot generation across a variety of commercial cell forms.

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8. ACRONYMS

GVSC	Ground Vehicle System Center
$\dot{Q}$	heat generation
I	Current
V_{OC}	Open Circuit Voltage
R_{Int}	Internal Resistance
SOC	State of Charge
V_T, V_{Dis}, E_{Dis}	Discharge Voltage
q	Capacity
Δg	Change in Gibbs Free Energy
Δh	Change in Enthalpy
Δs	Change in Entropy
n	Numbers of moles
F	Faraday’s Constant

α	Charge Transfer Coefficient	T	Absolute Temperature
j	Current density		
j_o	equilibrium current density		
j_l	Cell current limit		
r	Resistance/area		
R_u	Universal Gas Constant		