Determining Thermal Characteristics of Electric Vehicle Batteries After End of First Life

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Abstract
This paper presents an approach for thermal characterization of batteries (heat generation, heat capacity, and heat transfer). The first part of the paper outlines the theory and methodology to determine the heat capacity, thermal mass, heat generation rate, and heat transfer due to convection and radiation. The second part of the paper outlines the testing, design and verification of an energy storage system using re-purposed nickel metal hydride batteries from the end of electric vehicle life. The paper concludes with guidelines and considerations for designing a safe thermal system based on the thermal characteristics.

Keywords
Thermal Characterization — Thermal Management — Battery — Electrical Vehicles — Energy Storage Systems

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Contents

Introduction

When building a system which charges and discharges batteries such as in an Electric Vehicle (EV) or an Energy Storage System (ESS), the batteries must be thermally managed in addition to the electric control. Specifically, the system must be designed such that the temperature of the battery and the system remains below a specified threshold as it is an essential for achieving designed performance and life cycle of batteries.

In order to design battery pack management systems, the designers need to know the thermal characteristics of modules and batteries. Thermal characteristics that are needed include heat capacity of modules, temperature distribution and heat generation from modules under various charge/discharge profiles. [1]

Once the thermal characteristics are determined, designers must ensure that the temperature range and uniformity in a pack are met to obtain optimum performance. Specifically modules need to be operated at uniform temperatures because uneven temperature distribution in a pack leads to different charge/discharge behavior, which, in turn, leads to electrically unbalanced modules and reduced pack performance [2] This paper provides a summary of thermal characterization for re-purposed Nickel–metal Hydride (NiMH) batteries from Electric Vehicles.

1. Theory and Methodology

1. Heat Capacity and Thermal Mass

Determining the thermal mass (m_t) or the product of the specific heat (C_p)and mass (m) is required to complete transient analysis of battery modules and pack. It enables designers to understand how fast a pack or module cools down or heats from its initial temperature in a given surrounding. The average thermal mass can be estimated by a weight sum of the product of the specific heat and mass ($m_t = \Sigma C_{p,i} \times m_i$) of its material composition or by the use of a calorimeter which measures the actual effective heat capacity of a module. The direct measurement provides a more accurate estimate since the heat capacity capacity can change based on the initial state of change and temperature effects.

The principle for measuring capacity comes from the definition of heat capacity amount of heat required to cool or heat 1 kg of a material by 1 deg C. This can be done by placing a cell with known cell mass (m) and known initial cell temperature (T_m) in the calorimeter maintained at a constant temperature (T_c) and measuring the heat (Q) exchanged between the cell and the calorimeter. Once the cell temperature reaches the constant temperature of the calorimeter, the specific heat capacity can be determined using Equation 1.

$$C_p = \frac{Q}{m(T_m - T_c)} \tag{1}$$

To maintain accurate measurements, the heat released due to self-discharge of batteries during the testing [3] must be measured, and the calorimeter must be calibrated with a pure substance with known heat capacity.

If a calorimeter is not available for use, the specific heat can be determined from literature and should be generally between 500 and 1000 $J/kg^{\circ}C$ depending on the battery type and capacity [1].

2. Heat Generation Rate

Heat generated by a battery (Q) is due to work done by the resistive losses (I^2R) and the enthalpy changes due to the electro-chemical reactions during the charging and discharging. The heat transfer rate (q) is commonly generalized [4] by Equation 2 where the first term is Joule heating and the second term is heat generation due to entropy changes.

$$q = \dot{Q} = I(U - V) + I(T\frac{dU}{dT}) \tag{2}$$

Therefore, the heat generation of a module is affected by the following factors:

1. Chemistry of the battery
2. Construction of the cells
3. Initial and final state of charge
4. Battery temperature
5. Charge and discharge rate (and profile)

2.1 Analytical Method: Energy Balance

The governing equation outlining the energy balance in the battery is relating the heat generated by the battery in Equation 2 to the heat transfer to ambient conditions by convection [5]. The general form [6] can be equated to Equation 3

$$mc_{cell}\frac{dT_{cell}}{dt} = I^2R + T_{cell}\Delta S\frac{I}{nF} + Ah(T_{cell} - T_{amb}) \tag{3}$$

The use of this equation assumes a uniform cell temperature (lumped capacitance model) and must be validated through the use of a Biot number to apply the equation correctly. The Biot number ($B_i = \frac{hL_c}{k}$) compares the heat transfer occurring inside a body and its external surface temperature .

This method involves the use of typical values found in literature and is generally based on an ideal model for new batteries. Specifically, the thermal conductivity and heat transfer coefficient (k), entropy change (ΔS), specific heat capacity, internal resistance, and heat transfer coefficient must be found. Since batteries might be re-purposed and non ideal, alternative methods should be used to obtain a more accurate estimate.

2.2 Direct Method: Calorimeter

One direct method to determine heat generated by the resistive losses in the battery is by using a calorimeter. First, both the module at the desired state of charge and calorimeter are brought to steady state temperature. Then a load is applied to the module using a battery cycler at a specific discharge range (measured in coulombs C) with a fixed room temperature. The system (temperature of the module and test chamber) must be brought to equal. The self-discharge rate of the module was also measured at the end of charge or discharge at room temperature to correct for heat rate calculations [3].

Specifically, the module was discharged at a specific rate (in terms of coulombs) until it reached the minimum rated voltage limit and the calorimeter response (heat rate) for measured. As shown in Equation 4, by integrating the heat rate(in Watts) over time(seconds) where the heat (in Joules) generated during the discharge can be determined. The same can be done by charging at a fixed rate.

$$\int_{charged}^{discharged} \delta Q = Q_{charged \to discharged} \tag{4}$$

The experiment can be done at various charge and discharge rates and temperatures to get a better understanding of the heat generation in different charge and discharge cycles. The average cell heat rate can then be determined by the total heat generated (in Joules) divided by the total cycle time (in seconds) to reach 0% state of charge from 100% with a given discharge rate (in coulombs) as outlined in Equation 5

$$AverageCellHeatRate = \frac{HeatGenerated}{CycleTime} \tag{5}$$

In addition, the energy efficiency of the module under charge, discharge and cycling can be determined by using the electrical energy input/output and heat generated (the inefficiency):

$$Efficiency = [1 - \frac{HeatGenerated}{Energy(Input...Output)}] \times 100\% \tag{6}$$

2.3 Proxy Method: Coulomb Counting

Another alternative to determining the heat generated by the module is again using energy balance, but this time by empirically determining heat generation (energy loss) through the use of coulomb counting (measuring the current and voltage into and out of the battery during charging and discharging).

A coloumb (C) is the charge transported by a constant current of one ampere in one second (As). It can be related to energy (in joules) by multiplying by the voltage difference ($J = C \times V$). This can be empirically determined by measuring the voltage across the battery and measuring the voltage drop across a shunt resistor to determine current during the charging and discharging. The electric charge or number of coulombs/"coulomb count" can then be calculated by integrating the current over time as shown in Equation 7.

$$C = \int_{charged}^{discharged} I dt \tag{7}$$

The total energy input in the battery can then be calculated by multiplying the voltage to the number of coloumbs or directly inside the electrical power integral as shown in Equation 8.

$$W = \int_{charged}^{discharged} V I dt = C \times V \tag{8}$$

Total electrical energy lost due to heat generation (Q_{total}) during one charge and discharge cycle is equivalent to the heat generation assuming there is no other forms of energy (potential, mechanical etc.) in the system as shown in Equation 9.

$$Q_{total} = W_{in} - W_{out} \tag{9}$$

Energy losses due to heat will occur during both the charging and discharging of the batteries. By monitoring the input and output energy (though current and voltage) while charging and discharge the battery to fixed upper and lower voltages, the total energy lost due can heat can be calculated as shown in Equation 10.

$$Q_{total} = \int_{discharged}^{charged} V I dt - \int_{charged}^{discharged} V I dt \tag{10}$$

Once the total heat generated (Q_{total}) is determined, the average cell heat rate and efficiency can also be determined using Equations 5 and 6 respectfully. Of note, this rate and efficiency is on a full charge and discharge cycle, not an individual charge cycle and discharge cycle. When making design decisions, an approximate safety factor of two can be established by designing for the total heat generation in half a cycle (during only charging or only discharging).

3. Heat Transfer

Once the general thermal characteristics of the battery have been established, a system to ensure heat is safely and stably removed can be designed. This can be done by determining the heat transfer between the battery system and the environment. The three major heat transfer methods acting between the battery cell and the environment are the following:

1. Forced Convection
2. Natural Convection
3. Radiation

In the case of heat transfer from the batteries, if a fluid stream is present at a lower temperature than the batteries, heat transfer due to forced convection will generally dominate the other two methods. The section still outlines the behind each of the heat transfer methods and how they can be calculated.

3.1 Forced Convection

Heat transfer due to convection is proportional to temperature difference between the surface temperature $T_{cellexterior}$ and temperature of the fluid sufficiently far from the surface $T_{ambient}$, surface area (A_s) and heat transfer coefficient (h) and is expressed in Equation 11 as Newton's law of cooling.

$$\dot{Q} = hA_s(T_{cellexterior} - T_{ambient}) \tag{11}$$

To determine the heat transfer coefficient, a designer must first determine the the Reynolds number (Re) which is a relation of the inertial forces (upstream velocity $\vee$ and characteristic length (L_c) and viscous forces (kinematic viscosity ν)as shown in Equation 12.

$$Re = \frac{inertial forces}{viscous forces} = \frac{\vee L_c}{\nu} \tag{12}$$

The Renolds number helps establish if the flow is laminar or turbulent. If the Renolds is less than the critical Renolds number $Re_{cr} = 5x10^5$ then the flow can be assumed to be laminar unless the flow is obstructed by turbulators. Next, the heat transfer cofficient can be determined though the Nusselt ($Nu = \frac{hL_c}{k}$) which establishes the dimensionless heat transfer coefficient through the thermal conductivity of the fluid (k) and the characteristic length (L_c). The Nusselt number is usually a function of the Renolds numbers and the Prandtl number ($Pr = \frac{\nu}{\alpha} = \frac{\mu C_p}{k}$) which relates the molecular diffusivity of momentum to the molecular diffusivity of heat. The specific relation between the Nusselt number and the Prandtl and Reynolds number is dependant on physical parameters of the system.

3.2 Natural Convection

Heat transfer due to convection is also described by Equation 11 as Newton's law of cooling, but is related to the movement of fluid particles in the immediate vicinity of the hot object become warmer than the surrounding fluid resulting in a local change of density. The warmer fluid is replaced by the colder fluid creating free convection currents. These currents originate when a body force (gravitational, centrifugal, electrostatic etc.) acts on a fluid in which there are density gradients. The force which induces these convection currents is called a buoyancy force which is due to the presence of a density gradient within the fluid and a body force. The governing equations of natural convection and boundary conditions can be related by the use of the Grashof number (Gr_L) shown in Equation 13 as a relation between the gravitational acceleration (g), heat transfer surface area (A_s), and temperature difference between the cell exterior and ambient air.

$$Gr_L = \frac{g\beta(T_{cellexterior} - T_{ambient})L_c^3}{\nu^2} \tag{13}$$

Common empirical correlations [7] can be used to determine the average Nusselt number (for natural convection) by relating it to the Rayleigh number ($Ra_L = Gr_L Pr$) which is the product of the Grashof and Prandtl numbers. The Nusseult number for natural convection is commonly show in the form in Equation 14 with n as the constant exponent and c as the constant coefficient determined empirically based on the physical configuration.

$$Nu = \frac{hL_c}{k} = C(Gr_L Pr)^n = CRa_L^n \tag{14}$$

3.3 Radiation Heat Transfer

All substances at all temperature emit thermal radiation as an electromagnetic wave which does not require any material medium for propagation. In addition, all bodies which can emit radiation also has the capacity to absorb all or part of the radiation coming from the surroundings. Thermal radiation is absorbed by the body in the form of heat while part is reflected back into space, and part can be transmitted through the body.

A black surface is an ideal surface which absorbs all the incident radiation where the reflectivity and transmissivity is zero. The radiant energy emitted per unit time per unit area from the surface of the body is called the emissive power (e). The emissivity (ε) of a surface is defined as the ratio of the emissive power of the surface to the emissive power of the hypothetical blacksurface at same temperature (e_b.) as shown in Equation 15.

$$\varepsilon = \frac{e}{e_b} \tag{15}$$

The emissivity of the surface is also dependent of the nature of the surface and temperature, and the energy transfer by radiation is at a maximum when two surfaces transferring energy are in a vacuum. The basic equation for heat transfer by radiation relates the emmisivity, area of the body of radiation and the Stefan-Boltzmann constant ($\sigma = 5.676x10^{-8} W/mK$) and the temperature of the heat absorbing body as shown in Equation 16.

$$q_{rad} = A \times \varepsilon \times \sigma \times T^4 \tag{16}$$

A radiation heat transfer coefficient can be derived as analogous to the convective heat transfer coefficient by equating it to Newton's cooling equation as shown in Equation 17

$$h_r = \frac{\varepsilon(T_1^4 - T_2^4)}{T_1 - T_2} \tag{17}$$

The heat transfer due to radiation is also a function of view factor or the proportion of the radiation which leaves body A that strikes body B. This is dependent on the physical orientation of the objects and needs to be determined.

3.4 Combined Heat Transfer

If the heat transfer due to natural convection is in the same direction as the forced convection, then the total heat transfer will be the arithmatic sum as shown in Equation 18.

$$q_{total} = q_{conv} + q_{rad} = (\Sigma h)A_s(T_{cellexterior} - T_{ambient}) \tag{18}$$

2. Experiment, Results and Design

A experimental setup was made to monitor and log current, voltage, and temperature while charging and discharging a four cell battery module from 26.4V to 30V as shown in Figure 1. The combined graph of the initial test is shown in Figure 2, where the spike in temperature is due to manually touching the thermistor to ensure it is reading correctly.

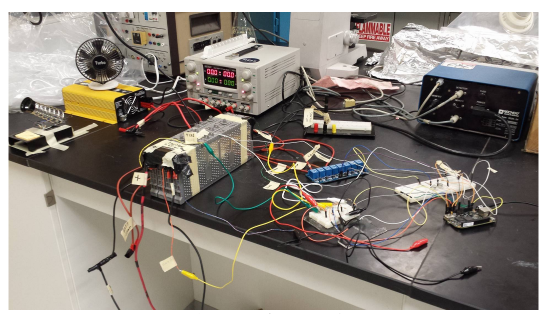

Figure 1. Photo of experiment setup.

Once temperature and voltage was measured and logged, current entering and exiting the battery was measured using a shunt resistor. A combined plot of the voltage and current across time during the charging and discharging of the battery is shown in Figure 3.

To understand the state of charge and general state of health of the battery, Coulomb Counting was done for the first charge and discharge cycle as shown in Figure 4.

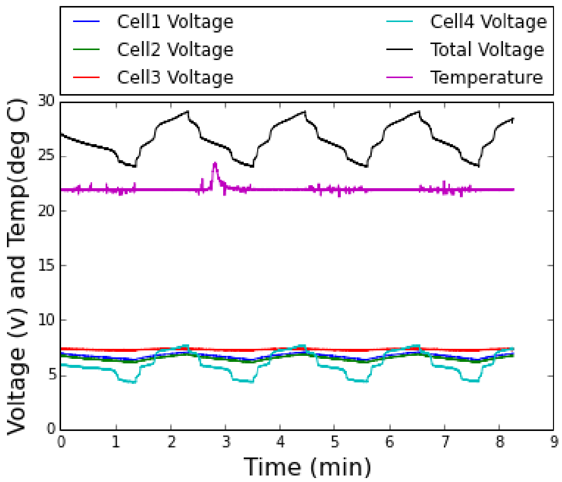

Figure 2. Voltage and current cycles during testing.

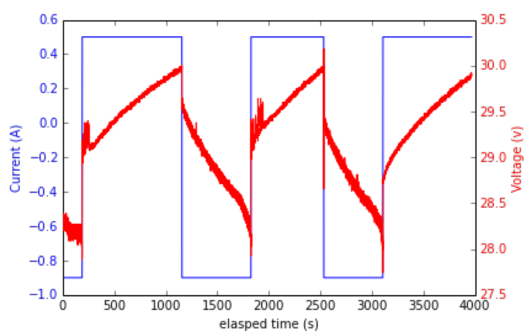

Figure 3. Current and Voltage Measurements on Battery.

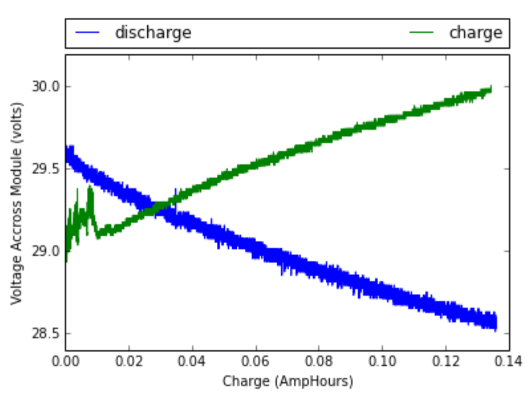

Figure 4. Coloumb Counting on Battery.

4. Mechanical and Thermal Design

Figures 5 and 6 show the preliminary design of the battery enclosure. The enclosure is to ensure all the battery modules and other electrical components may to be stored safely and protected from external impacts. There are ports at the bottom of the ensure for fans and airflow, and vents at the top for hot air and hydrogen (released from the batteries) to escape.

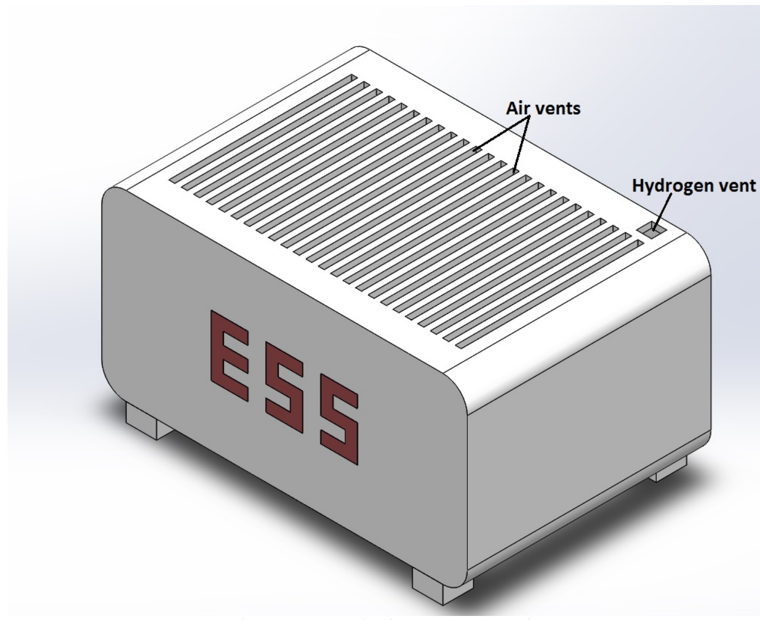

Figure 5. Enclosure Rendering - Front View

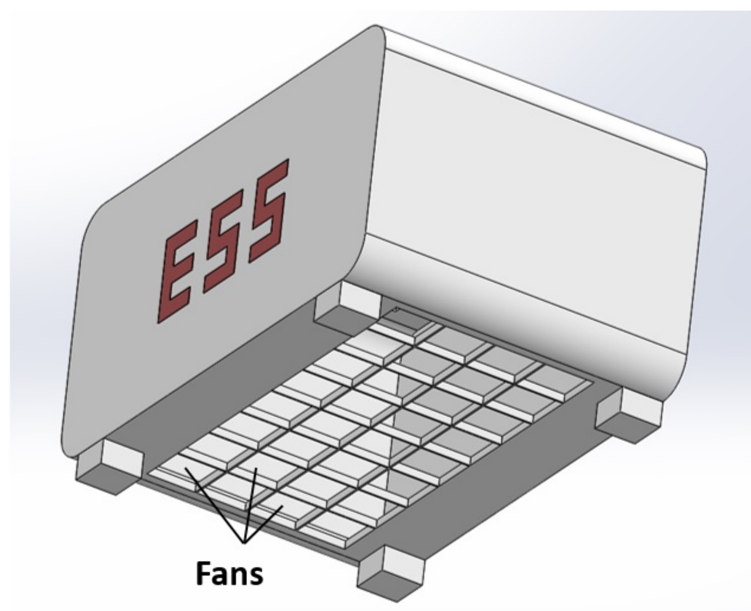

Figure 6. Enclosure Rendering - Bottom View

5. Determining the Heat Generation Rate

Based on the testing, it was found that the temperature will increase as a function of time. This is expected since heat generated by a battery (Q) is due to work done by the resistive losses (I^2R) and the enthalpy changes due to the electro-chemical reactions during the charging and discharging as outlined in the previous section. This is commonly generalized [4] by the following equation:

$$q = I(U - V) + I(T\frac{dU}{dT})$$

Where the first term is Joule heating and the second term is heat generation due to entropy changes. Therefore, the heat generation of a module is affected by the following factors chemistry of the battery, construction of the cells, initial and final state of charge, initial battery temperature, charge and discharge rate (and profile). The next two subsection outlines the two methods which were used to determine the heat generated.

5.1 Coloumb Counting/ Energy Balance

The proxy method described is though the use of coulomb counting and solving for the energy going into the battery and energy discharged by the battery under fixed current. The difference in energy (into and out of the battery system) is the energy lost due to heat.

$$Q_{lost} = \int_{discharged}^{charged} VIdt - \int_{charged}^{discharged} VIdt = 520.73J$$

The average rate of heat generation can then be calculated by dividing by the difference in time (time to charge and discharge the battery):

$$q_{gen} = \frac{Q_{lost}}{\Delta t} = \frac{520.73J}{1156.6 + 1701.04s} = 0.182Watts$$

5.2 Ohmic Losses from Internal Resistance

Energy lost in a battery [8] can also be related to the resistive losses of the circuit equivalent of the battery:

$$q = P_j(t) = R_\Omega i(t)^2 + \frac{v_{tc}(t)^2}{R_{tc}} + \Sigma_{n=1}^{15}\frac{v_n(t)^2}{R_n} = R_{int}i(t)^2$$

Therefore a safer and harsher method to determine the loss due to heat is to estimate the internal resistance of the module (R_{int}). The correct method to determining the maximum internal resistance is to conduct hybrid pulse power characterization (HPPC). HPPC indicates that R_{int} is a function of the state of charge (SOC) [9], and can also be related to the temperature of the module. By characterizing the worst case internal resistance, a designer can establish both the maximum energy lost due to heat and the SOC and temperature which will cause this. In addition, a designer can design for optimal operation by maintaining an ideal SOC and temperature if feasible.

Since an HPPC was not conducted due to simplicity and time restrictions, the internal resistance can be estimated by using the voltage increase during the step change from discharging charging:

$$R_{int} \cong \frac{V_2 - V_1}{I_2 - I_1} = \frac{29.5 - 27.9}{0.5} = 3.2\Omega$$

By using a one sided change in current (0.5A) instead of the total change from charge to discharge (1.4A net), the estimate will be conservative (in terms of safety) since the energy loss calculated will be greater than in reality. This is important since the internal resistance is not constant and is rather a function of the current temperature, state of charge and other conditions. By establishing a larger than normal resistance, it create a worst case with an inherent safety factor.

The resistive losses can then be equated to the heat transfer by multiplying by the maximum current draw squared:

$$q = \Delta I^2 R = 1^2 \times 3.2 = 3.2W$$

6. Heat Transfer

6.1 Convection

When designing a thermal management system, the modules will be cooled by convection through air from the bottom as shown in Figure 7. Air drawn from a fan will have a temperature of T_∞ , speed u, and heat transfer coefficient of h. Air is being blown from a 60 mm x 60 mm x 15 mm fan and is assumed to pass through a quarter of the length of the module. The surface temperature the module has to reach before the fan is turned on is 30°C. However, the cut-off temperature at which the module will stop operating is 50°C. With the fan selected, 4 fans is needed to cool 3 modules stacked next to each other. The module will be modeled as a flat plate with length as 106mm.

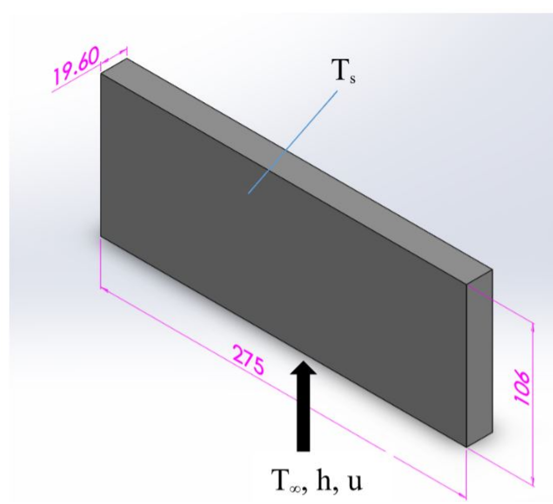

Figure 7. Battery Cell under convection heat transfer

Assumptions:

1. Steady state

2. Turbulent flow since dimples act as turbulators
3. Air is an ideal gas with constant properties

Properties of air evaluated at 22°C:

- $k_{air} = 0.0259 \frac{W}{mK}$
- $\nu_{air} = 1.545 \times 10^{-5} \frac{m^2}{s}$
- $Pr_{air} = 0.708$

Properties of fan:

- Max airflow = 13.06 cfm (cubic feet per minute)
- Assuming flow passing through rectangular 60mm x 60mm duct, velocity of air is 1.71 m/s.
- Power needed to operate fan is 0.7 W.

Reynold's number is:

$$Re_L = \frac{\vee L}{\nu} = \frac{(1.71)(0.106)}{1.545 \times 10^{-5}} = 11,732$$

Nusselt number assuming isothermal surface and turbulent flow:

$$Nu_L = 0.0296 \times Re_L^{\frac{4}{5}} \times Pr^{\frac{1}{3}} = 0.0296(11732)^{\frac{4}{5}}(0.708)^{\frac{1}{3}} = 47.5$$

Heat transfer coefficient, h:

$$h = \frac{k}{L} Nu_L = \frac{0.0259}{0.106} \times 47.5 = 11.61 \frac{W}{m^2 K}$$

Heat transfer by convection from part of one surface:

$$q = hA_s(T_s - T_\infty) = (11.61)(0.106)(0.06)(50-22) = 2.07 \text{ W}$$

With 4 fans, the total heat transfer by convection from one surface is 8.27 W.

To see the effect of natural convection, the ratio between the Grashof number and Reynold number squared is calculated.

$$Gr = \frac{\beta g (T_s - T_\infty) L^3}{\nu^2} \text{ where } \beta = \frac{1}{T_f} \text{ and } T_f = \frac{T_s + T_\infty}{2}$$

Using the given values, Grashof number is equal to 4,435,363. The ratio is thus calculated to be,

$$\frac{Gr}{Re^2} = 0.03 \ll 1$$

Therefore, forced convection from the fan dominates and contributes to most of the heat transfer by convection.

6.2 Radiation

Since the modules will be stacked closely next to each other and all the surfaces are assumed to be diffuse-Gray surfaces, the net radiation between the modules is zero. Radiation is only effective for the surfaces exposed to the surroundings and only the 2 modules at each end will have more heat radiated outwards than the rest of the modules in the pack. Assuming the battery pack is placed in a large isothermal case with a wall temperature equal to room temperature, the radiation is calculated by:

$$q_{rad} = \sigma \varepsilon A_s (T_s^4 - T_w^4)$$

For the modules in the middle of the pack, surface area that can lose heat through radiation is calculated to be $A_s = 0.0151 m^2$. The module at each end of the pack has an extra surface area of $A_s = 0.0292 m^2$ that can lose heat by radiation. The emissivity of highly polished aluminum is $\varepsilon_{alum} = 0.039$ while that of polypropylene is $\varepsilon_{polyprop} = 0.97$.

Heat transfer by radiation is thus calculated to be:

$$q_{rad} = (5.67 \times 10^{-8})(0.97)(0.0151)(323^4 - 295^4) = 2.75 \text{ W}$$

For the modules at each end, heat transfer is calculated to be:

$$q_{rad} = 2.75 + (5.67 \times 10^{-8})(0.039)(0.0292)(323^4 - 295^4) = 2.96 \text{ W}$$

Combining the convection and radiation terms, the total heat transfer from the modules in the middle of the pack is 19.29 W. The total heat transfer for the module at each end is 19.5 W.

7. Heat Capacity and Transient Analysis

Since a calorimeter was not available, the heat capacity of the 6.5 Ah NiMH module was determined as $C_p = 521 J/kg/^oC$ from literature [1]. Since the mass of the module is $= 1.045 kg$, the thermal mass can be solved for:

$$T_m = C_p \times m = 521 \times 1.045 = 544.445 J/^oC$$

When designing a the thermal management system, the designer must ensure that the system cools down the heat generated by the battery modules as well as maintain the temperature of the modules as close to room temperature (or optimal temperature based on Rint characterization) as possible. Assuming constant airflow provided by the fan, the heat dissipated by convection and radiation needs to be greater than the heat generated. At 50°C, the module will enter an open state where it will stop charging or discharging and so the thermal management system needs to cool down the module to room temperature before normal operation proceeds.

The heat capacity of the module would determine how much energy needs to be taken out in order to bring down the module to room temperature. This is given by the following equation:

$$Q = mC_p(T_s - T_\infty)$$

For worst case scenario when T_s= 50°C and with a C_p = $521\frac{J}{kg°C}$, the heat capacity of the module (of mass m = $1.045kg$) is:

$$Q_{50} = 1.045 \times 521 \times (50-22) = 15244 \text{ J}$$

The time it takes for the current fans to bring the module back to room temperature is given by:

$$t_{50} = \frac{Q_{50}}{q_{diss}} = \frac{15244}{19.29} = 790 \text{ seconds} = 13.2 \text{ minutes}$$

Given the heat generated from the module (at the worst case) is 3.2 W and with a battery temperatures of 30°C and 40°C, time taken to cool down the module to room temperature can also be calculated:

$$t_{40} = \frac{Q_{40}}{q_{diss}-q_{gen}} = \frac{1.045\times521\times(40-22)}{19.29-3.2} = 609.1 \text{ seconds} = 10.2 \text{ minutes}$$
$$t_{30} = \frac{Q_{30}}{q_{diss}-q_{gen}} = \frac{1.045\times521\times(30-22)}{19.29-3.2} = 270.7 \text{ seconds} = 4.5 \text{ minutes}$$

While the system can be considered to have poor transient performance (as the time to bring the temperature down is long), this can be actively managed by varying the fan speed to ensure the heat transfer rate is greater than the heat generation rate.

The purpose of this exercise was to determine the margins of scale for the worst case operation. After a better understanding of the Rint as as function of the state of charge and temperature, a better fan control system can be designed to ensure transient performance for maximum efficiency and performance.

Conclusion

Given the task of designing a system which charges and discharges batteries such as in an Electric Vehicle (EV) or an Energy Storage System (ESS), designers must ensure that the batteries are thermally managed such that the temperature of the battery and the system remains below a specified threshold as it is an essential for achieving designed performance and life cycle of batteries. The first step in the design is the thermal characterization of the battery and this paper outlined the methology and associated theory on how to conduct a basic thermal characterization of the system. First the heat generation rate was estimated using both an energy balance and ohmic loss due to internal resistance methods. Next heat transfer was determined through radiation and convection based on the design of the battery cells and characteristics of fans. Finally the heat capacity and basic transient analysis was done to verify the thermal stability of the system. It was concluded that the design designed was thermally stable, but future internal resistance characterization and transient analysis must be conducted for improved design.

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