AIAA-2000-2818

QUICK CHARGE BATTERY WITH INTERNAL THERMAL MANAGEMENT

Ronald J. Parise
Parise Research Technologies
101 Wendover Road
Suffield, CT 06078

ABSTRACT

Thermoelectric generators (TEGs) are unique solid state components that can be used as a cooling device when supplied with electric power. These coolers can be built in many configurations for unusual applications where parasitic thermal energy must be managed. Such an application is in secondary (rechargeable) batteries where thermal build-up extends recharge time and reduces battery life. These maladies increase system operating costs and add inconvenience to the operation of the battery-powered device.

In particular, battery usage in electric vehicles has been especially disappointing since recharge time needed between limited vehicle travel distances (approximately 160 km/100 mi) are not acceptable to consumers. Vehicle down-time has discouraged usage of this pollution-free means of transportation.

Higher charge rates would result in lessening vehicle recharge time. However, these charge rates are undesirable due to the thermal build-up in the battery. The bulk and mass of a typical electric vehicle battery, usually a lead-acid battery, does not lend itself to being cooled quickly, strictly from external surfaces. Therefore a means of removing the thermal energy at the point of production, internal to the battery, can be accomplished using thermoelectric coolers in the battery case, in cell partitions and/or between positive-negative plate pairs where the heat is produced.

Although the lead-acid battery is considered in this study, any other battery type with thermal management problems can be considered, including fuel cell applications.

A preliminary study utilizing this unique thermal management scheme inside the battery is presented. The simple model investigates the parameters that influence parasitic heat build-up in a lead-acid battery.

INTRODUCTION

There are several sources of heat generation in secondary batteries that result in thermal build-up. Some are due to particular battery types or designs. However, there are two main causes inherent to all batteries. One is electrical I^2R losses during discharge or recharging. Quick recharge times requiring high charging rates can result in very large losses. Typically, with the resulting thermal build-up in the battery, charging must be interrupted to allow the heat to dissipate, extending recharge time.

The second source of thermal energy in electrochemical batteries is the various reactions that take place during both discharge and charging. For example, in lead-acid batteries the chemical reaction that produces the electromotive force, lead and lead dioxide with sulfuric acid, causes an exothermic heating of the battery. During charging, this is an endothermic reaction that actually cools the battery. However, during typical recharge rates, the I^2R losses more than offset this cooling, resulting in a net increase in thermal energy. And for very high charging rates, the cooling effect becomes insignificant.

Thus the metal grid plates are the prime source of heat production, both at their surface where the chemical reactions take place and internally where the current flows and the electrical resistance causes the heat generation. This is the primary location and source of heat in the battery. And this is why the heat is so difficult to remove. The bulk and configuration of large batteries do not lend themselves to easy heat removal.

The subsequent heat build-up produces an obvious temperature increase in the battery. This elevated operating temperature can cause physical damage and/or electrolyte changes that will adversely affect the operation of the battery. Also, the electrical resistance will increase, causing the performance of the battery to deteriorate further.

This heat generation takes place most internal to the battery where heat transfer augmentation is almost impossible to apply without significantly altering the design of the battery. However, if cooling can be provided at the point of this heat generation, improved recharge times and battery performance will result.

The application of thermoelectric coolers at the source of waste heat production will aid in battery longevity and increase practical usage of the battery, especially in the automotive industry.[1] The coolers can be configured to be positioned in any or all of several locations internal to the battery for the best results of heat removal.

First, the TEG coolers can be installed between the positive and negative grid plates of the cell pairs. Construction has to be such that the electrolyte can still flow easily between the plates during both discharge and recharge of the battery. In this location, the coolers are in good thermal contact with the prime source of heat production, the metal plates.

Second, the TEG coolers can be positioned between positive/negative plate pairs. This reduces the influence of electrolyte flow between the positive and negative plates. This is not as integral to the origination of the heat generation, but well within contact of that main location.

Third, the TEG coolers may be placed in cell partitions or battery case walls. In this location, there is no effect on electrolyte flow between plates. The battery still enjoys the cooling effects of close proximity to the heat source.

Figure 1 illustrates the thermoelectric cooler between a pair of positive/negative grid plate pairs. The cold junctions of the TEG cooler are in intimate thermal contact with the electrolyte and the surfaces of the grid plates through the cold junction plates. The cold junction plate is a good thermally conducting square or rectangular ring that allows the free flow of electrolyte between the grid pairs.

The warm junctions of the TEGs are on the exterior of the battery. Cascading of elements can facilitate the hotter junctions being outside the core of the battery where heat transfer augmentation can be utilized to remove the waste heat.

Under certain operating conditions, the interior of the battery may require heating. In this application, current flow can be reversed in the TEG to control the battery internal temperature. Obviously control circuitry would be needed to maintain a specified temperature.

A two-phased approach will be used to investigate the effectiveness of the TEG cooler inside the battery. The basic model developed here will include only the heat generated by I^2R losses. The chemical reactions that take place in a lead-acid battery can be of the same order of magnitude as the I^2R losses,[2] but will not be considered in this simple model. This study will focus initially on the overall battery-cooler concept.

The second phase will include chemical reactions that influence the overall thermal energy in the battery, geometric considerations and battery types other than lead-acid. This advanced model, considered for future research, will be used to optimize the TEG cooling effect for locations in the battery, battery type and TEG cooler configuration.

MODELING APPROACH

A two-dimensional, steady-state thermal model with a known, uniform heat generation will be developed to determine the temperature gradient in the region between the two grid plate stacks. The model takes advantage of symmetry for a square or rectangular battery design. Figure 2 shows the section to be modeled for the battery plates. The TEG cooler is located between two positive/negative plate pairs in intimate thermal contact with the two plates, situated in the electrolyte. Although in actuality the heat is generated in the metal plates, the model will consider the bulk of the generation to occur in the adjacent electrolyte section, around which the cooling plate is located.

Shown in Figure 3 is the configuration used for the thermal analysis. The heat removal by the TEG cooler is depicted by the two adjacent boundaries with the constant heat flux. The cooling plate can be configured to maintain a constant heat flux along these two sides. The primary concern is the maximum temperature that the battery will achieve normally during charging. This temperature would be at the centerline of the battery, at x=0 and y=0 in the model.

This initial study shows the effect of the TEG cooler with a one-dimensional model of the battery cooler. The analysis does present the solution to the two-dimensional case, but only the results to the 1-D case are presented here.

The 1-D model is used for the cooling of a typical lead-acid battery with a TEG cooler. This configuration is shown in Figure 4(A). The material of the battery in thermal contact with the cold junction plate is the electrolyte between the cell grid plates. The full width of the battery is typically 16cm. With two cooling plates in the battery, the distance from the centerline to the cold junction plate is L=4cm. The maximum allowable internal temperature of the battery is 350K.

The TEG cooler is modeled as a single junction with bismuth telluride. The elements are 0.1cm x 0.5cm and 4cm long. The hot junction of the TEG cooler is in the ambient at T_{amb}=300K. The internal resistance[2] of the battery is assumed to be 0.0025ohms and the charging current varies from 0 to 2.0amps.

The maximum internal temperature of the battery is considered for three cases, two with no TEG cooling and the third with the TEG cooler. In the first two cases, the external temperature of the battery is maintained at 305K and 310K, respectively. This is analagous to the battery being cooled by natural or forced convection when the ambient temperature is 300K and there are no TEG coolers. In the third case, the TEG cooler is utilized to maintain the cold junction plate at a temperature T_c, hence, the heat is removed by the TEG cooler. Figure 4(B) shows the parameters used for the model.

The maximum temperature that the battery will experience is at x=0, the furthest point from the cooling surface. This is the centerline location of the cold junction plate, or the axis of symmetry. In the model, this is depicted by T_{CL}.

EQUATION DEVELOPMENT

HEAT CONDUCTION MODEL

The two-dimensional Fourier Law for heat conduction[3] in the battery with internal heat generation, q''', is:

$$\partial^2T/\partial x^2 + \partial^2T/\partial y^2 + q'''/k_a = 0, \quad (1)$$

where T is the local temperature at (x,y) and k_a is the thermal conductivity of the battery electrolyte. The generation term is

$$q''' = I_{batt\ chrg}^2 \times R_{batt}/\mathrm{Volume},$$

where $I_{batt\ chrg}$ is the charging amperage to the battery, R_{batt} is the internal resistance of the battery, and Volume is the dimensional volume of the generation region. For the 2-D case, Volume=A_{batt}, that is, the area of the 2-D battery per unit depth.

The centerline for the region of cooling in the battery is the axes of symmetry. The boundary conditions at the centerline are:

at x,y = 0:

$$\begin{aligned} \partial T/\partial x|_{x=0} &= 0 \\ \partial T/\partial y|_{y=0} &= 0 \end{aligned} \qquad (2)$$

Internal to the battery and where the cold junctions of the TEG cooler are in thermal contact with the cooling plate, the boundary is maintained at a constant temperature T_c. Therefore the boundary conditions are:

at $x = l$, $y = L$:

$$\begin{aligned} T(l) &= T_c \\ T(L) &= T_c. \end{aligned} \qquad (3)$$

The solution to the two-dimensional heat conduction equation[3] is shown in Appendix A. Equations (A1) - (A3) provide the temperature distribution throughout the battery region with the cold junction plate maintained at a constant temperature T_c. The maximum temperature in the battery, at x,y=0, can be calculated from Equation (A4). Equations (A5) and (A6) relate the heat flux that must be removed at the boundaries, Q_x and Q_y, by the TEG cooler.

ONE-DIMENSIONAL MODEL

In this initial study, the 1-D model is used. The solution for one-dimensional heat flow in the battery is:

$$T(x)=(q'''L^2/2k_a)[1-(x/L)^2]+T_c \qquad (4)$$

where T_c is the temperature of the boundary at x=L. With the TEG cooler, T_c is the temperature of the cold junction plate. When no TEG cooler is present, T_c is the applied temperature at this boundary.

The boundary conditions for the 1-D case are the same as the 2-D case. That is, the boundary at x=0 is an axis of symmetry and the cold junction plate is at T_c.

For the charging of the battery in the 1-D case:

$$q''' = I_{batt\ chrg}^2 \times R_{batt}/L_{batt} \qquad (5)$$

This is the heat addition per length of battery due to charging.

THERMOELECTRIC EQUATIONS

The Seebeck cooling effect of the TEG junction is also influenced by the heat generation in the TEG elements and the conduction of heat from the hot to the cold junctions.[4] Therefore the heat removed at the cold junction is:

$$q_c = \alpha T_c I_{cool} - 1/2\, I_{cool}^2 R_{cool} - \kappa_c \Delta T, \qquad (6)$$

where

$$R_{cool} = (\rho_n l_n/A_n) + (\rho_p l_p/A_p)$$

and

$$\kappa_c = (\lambda_n A_n/l_n) + (\lambda_p A_p/l_p).$$

The physical properties of the p- and n-type TEG materials are the combined Seebeck coefficients of the two materials, $\alpha=|\alpha_p|+|\alpha_n|$; the thermal conductivities, λ_p, λ_n; and the thermal resistivities, ρ_p, ρ_n. The geometry of the TEG elements are the lengths of the elements l_p, l_n and the areas A_p and A_n.

Equation (4) is used to calculate the heat rate, dT/dx at x=L, due to heat generation in the battery, to determine q_c. The value of I_{cool} that will maximize the heat removed,

q_c, by the TEG cooler is

$$I_{coolmax} = \alpha T_c / R_{cool}. \qquad (7)$$

Therefore, with the required q_c known and $I_{coolmax}$ chosen to maximize the heat removal, T_c can be calculated. With T_c known, $T(0)=T_{CL}$ is then calculated from Equation (4).

RESULTS

The maximum internal temperature of the battery due to heat generation is shown in Figure 5. The temperatures T_{CL}, at x=0 or the centerline of the cold junction plate, are shown with and without the benefit of the TEG cooler. The surface temperatures of 305K and 310K correspond to the temperature of the cold junction plate in the model, T_c. For the two cases where there is only convection cooling at the battery surface (no TEGs), the internal temperature exceeds the maximum allowable temperature of 350K. But when the TEG cooler is utilized, the maximum internal battery temperature remains well within the acceptable limits. The figure also shows the relative temperature of the TEG cold junction plate, T_c, increasing only slightly over the full range of charging rates.

When the charging rate for the battery is increased from 0.4 to 0.8, the battery with the TEG cooler still maintains an internal temperature well below what is acceptable. The battery with only convection cooling at the surface is no longer able to meet this requirement.

DISCUSSION

For the cases where the internal maximum temperature exceeds the allowable limit, the charging rate would have to be reduced. This would result in an increased recharge time of the battery. Otherwise the longevity and performance of the battery would be reduced over time if operated at this elevated temperature.

However, utilizing the TEG cooler indicates that the charging rate is well within the acceptable limits for the internal temperature of the battery and in fact the charging rate can be increased further to hasten the recharge time. For the example cited, battery recharge time can be reduced 40% by providing internal cooling to the battery.

CONCLUSIONS

The addition of the TEG cooler increases the charging rate that the lead-acid battery can endure. This will decrease the amount of time that the battery is out of service for recharge. Or, by better monitoring and controlling the internal temperature of the battery, the longevity and performance of the battery may be improved greatly. Therefore the effectiveness of internal cooling for lead-acid batteries can show promise in many applications where recharge cycle time must be reduced for the usefulness of the battery powered device to be practical.

REFERENCES

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3. Arpaci, V. S., Conduction Heat Transfer, Addison-Wesley, Reading, MA, 1966.

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Appendix A
2-D Temperature Equations

The temperature distribution in a quadrant of the battery of width 2L in the x-direction and height of $2l$ in the y-direction is:

$$\frac{T(\eta,\xi)-T_c}{q'''L^2/k_a} = \frac{1}{2}(1-\eta^2) - 2\sum_{n=0}^{\infty}\frac{(-1)^n}{\lambda_n^3}\,\frac{\cosh(\lambda_n\xi)}{\cosh(\lambda_n\alpha)}\,\cos(\lambda_n\eta), \qquad (A1)$$

where

$$\alpha=\frac{l}{L}, \qquad \eta=\frac{x}{L}, \qquad \xi=\frac{y}{L}, \qquad (A2)$$

and

$$\lambda_n = (n+\frac{1}{2})\,\pi. \qquad (A3)$$

The maximum temperature in the battery, T_{CL}, at $(\eta,\xi)=(0,0)$:

$$\frac{T_{CL}-T_0}{q'''L^2/k_a} = \frac{1}{2} - 2\sum_{n=0}^{\infty}\frac{(-1)^n}{\lambda_n^3\cosh(\lambda_n\alpha)} \qquad (A4)$$

The heat flow rate through one quadrant of the battery (adjacent sides) is:

$$\frac{Q_x}{q'''L^2/k_a} = \alpha - 2\sum_{n=0}^{\infty}\frac{(-1)^n}{\lambda_n^3}\,\tanh(\lambda_n\alpha)\;\sin(\lambda_n), \qquad (A5)$$

$$\frac{Q_y}{q'''L^2/k_a} = 2\sum_{n=0}^{\infty}\frac{(-1)^n}{\lambda_n^3}\,\tanh(\lambda_n\alpha)\;\sin(\lambda_n)\,\cdot \qquad (A6)$$

Figure 1: Cooler Between Plate Pairs.

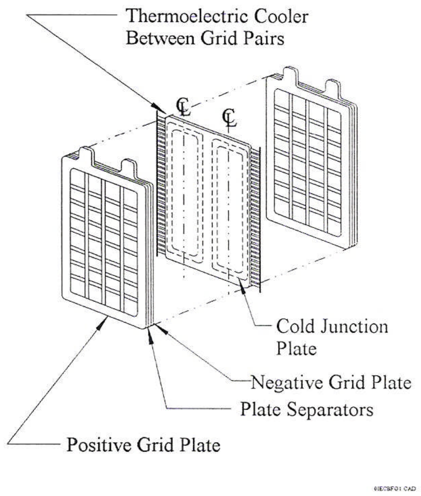


Figure 2: Cooler Location Between Grid Pairs.

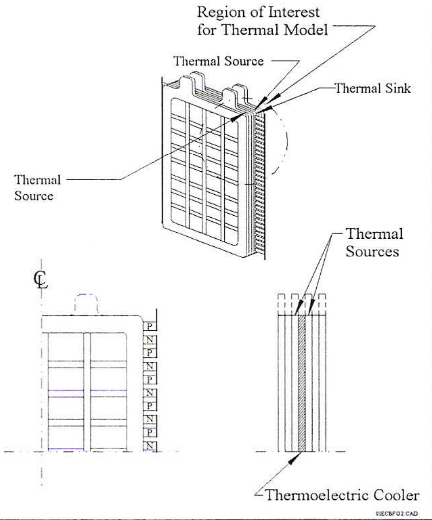


Figure 3: Basic Model Configuration for Thermal Analysis

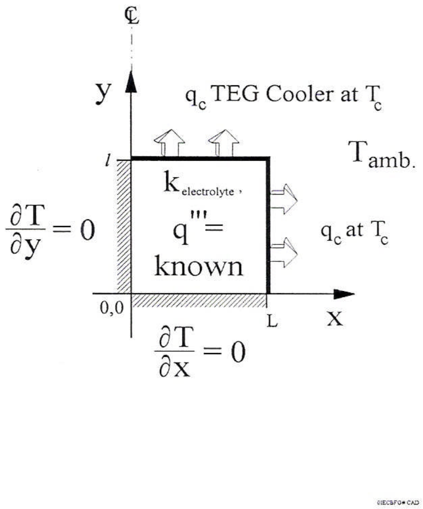
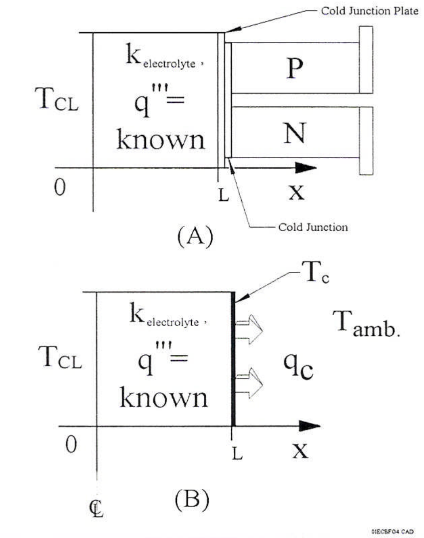


Figure 4: Basic Configuration for the 1-D Model.



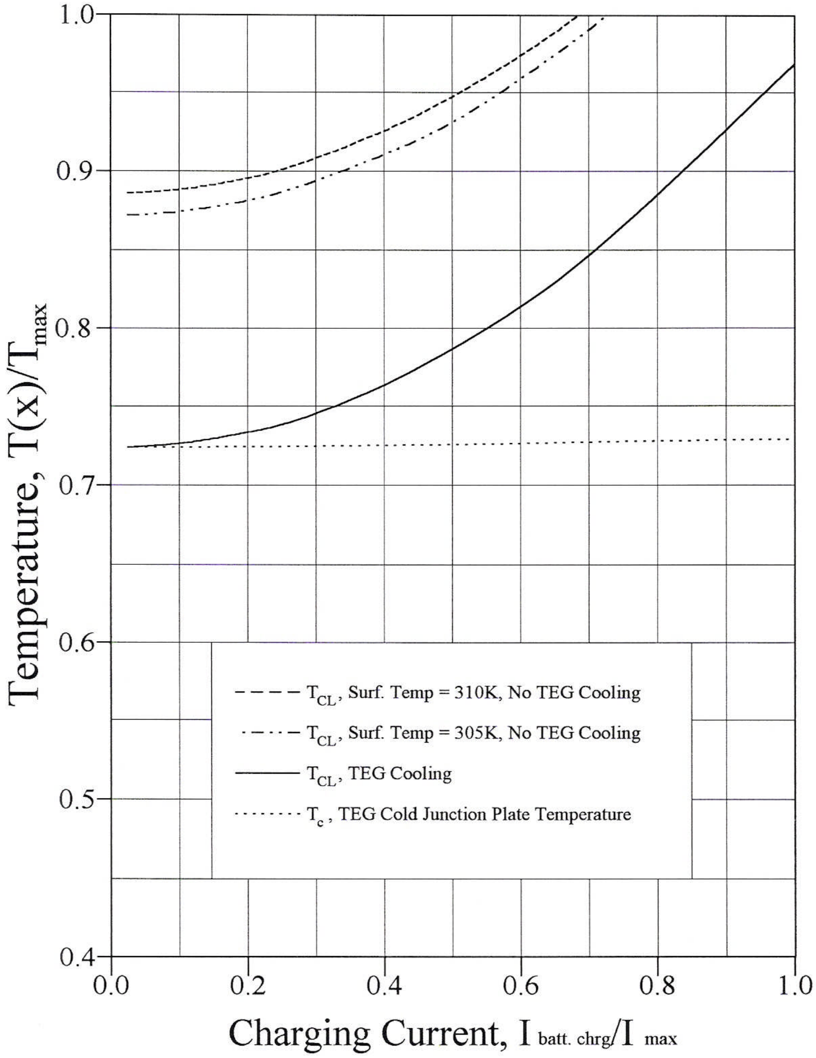


FIGURE 5: Battery Temperature vs. Charging Current