A Unique Calorimeter-Cycler for Evaluating High-Power Battery Modules

Ahmad A. Pesaran[1], Donald J. Russell[2], John W. Crawford[2], Robert Rehn[1], and Edwin A. Lewis[2,3]

[1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401, ahmad_pesaran@nrel.gov
[2]Calorimetry Sciences Corporation, 515 East 1860 South, Provo, UT 84603, calscorp@aol.com
[3]Brigham Young University, Provo, UT 84602

ABSTRACT

Battery thermal management is critical for high-power battery packs commonly used in electric vehicles (EV) and hybrid electric vehicles (HEV). To design battery thermal management systems properly, obtaining accurate heat generation data from battery modules is essential. To measure heat generation from full-size, multiple-cell battery modules, we developed and tested a custom-made calorimeter for large modules. Battery modules with dimensions up to 21 cm x 39 cm in cross section and 20 cm in height can be placed in the cavity of the calorimeter for measuring heat generation rates from 1 W to 100 W with the battery operating at -30°C to +60°C. The instrument is capable of measuring heat effects as small as 10 joules with accuracy of 5%. A state-of-the-art high power battery cycler is used to cycle the modules in the calorimeter. This paper provides a description of the calorimeter, calibration test results on its performance, and test results from a module simulating a HEV lead-acid battery.

Introduction

The performance and life-cycle costs of electric vehicles (EV) and hybrid electric vehicles (HEV) depend on the performance and life of their battery packs. It is important to regulate battery pack operating temperature because it affects performance (power and capacity), charge acceptance (during regenerative braking), and vehicle operating and maintenance expenses [1]. Today's EVs and HEVs require thermal management systems to maintain their battery packs within the desired temperature range. Because HEV batteries have a higher specific power and experience a more aggressive charging/discharging profile than those of EVs and many other applications, more heat is generated. Figure 1 shows a power profile for a battery pack in a series HEV during a typical driving cycle [2]. Note how quick and large the energy peaks are going in and out of the battery. A well-designed thermal management system is critical for HEV battery packs. To develop such a system, it is necessary to know how much heat is generated by a battery module during various charge/ discharge cycles and whether the heat was generated electrochemically or resistively. A special purpose purpose calorimeter is needed to accurately measure the heat generated from battery modules.

Battery and electrochemical calorimeters have been used by many investigators to characterize the behavior of cells, electrodes, and electrochemical reactions [3,4,5,6]. Most of these studies used small scale samples and cells to conduct experiments [7,8]. A limited number of previous studies deal with large battery calorimeters. After a detailed analysis of

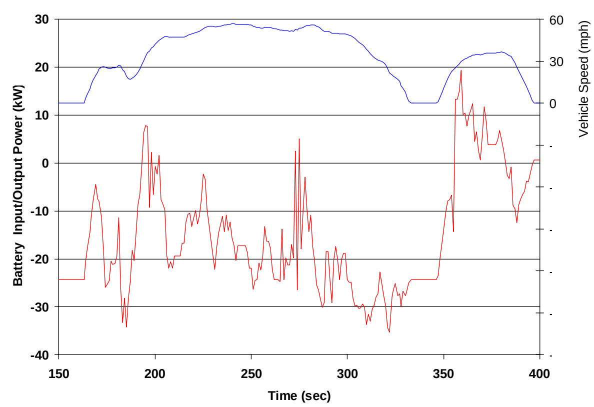

Figure 1. A Typical Charge-Discharge Profile for a Battery Pack in a Series Hybrid Electric Vehicle [2]

battery pack thermal management requirements [1] as part of the U.S. DOE Hybrid Vehicle Propulsion Systems Program, we identified a need for accurate calorimetry data for large battery modules of interest. Our reasons for obtaining the calorimetry data were:

- To obtain accurate heat generation data for modules developed by the HEV Program participants under different modes of system operation, battery cycling, and operating temperatures
- To measure round-trip energy efficiency (i.e., to distinguish energy stored from heat generated) for use in estimating vehicle energy consumption

- To validate and calibrate a module thermal model [1] developed by the National Renewable Energy Laboratory (NREL) and an electrochemical model developed by another HEV program participant
- To measure heat generation when the module is experiencing thermal runaway and cell reversal
- To obtain a performance signature over time to evaluate the effects of aging and cycling
- To evaluate physical and electrochemical design changes that could lead to better battery modules
- To assist in evaluating battery pack designs that leads to better battery packs and hence improved HEV performance.

Off-the-shelf calorimeters could not be used to obtain data in support of the above activities, because most are designed for testing small cells (less than C size). To characterize the behavior of large modules and avoid any loss of accuracy due to scale-up from small cells, a custom-made calorimeter was needed. In addition, it was determined that with accurate data on the heat generation and thermal performance of large full-scale modules under realistic conditions, improved modules and battery packs could be designed for the specific applications.

NREL determined the specifications necessary for a battery calorimeter to measure heat generation with an accuracy of better than 5%. A competitive contract was awarded to Calorimetry Sciences Corporation (CSC) to design and fabricate a calorimeter for full-size battery modules. The calorimeter was developed and tested for baseline performance by using integrated internal calibration heaters. A simulated battery module based on a lead-acid HEV module developed by another HEV program participant was fabricated and tested in the calorimeter to establish the calorimeter performance and accuracy for module measurements. NREL acquired a state-of-the-art, high-powered battery cycler to charge/discharge modules in the calorimeter while simulating typical EV and HEV driving profiles. In the following sections, we present specifications for the calorimeter and the cycler, explain the baseline performance of the calorimeter, show typical test results with the simulated HEV battery module, and describe future experiments to be conducted with HEV lead-acid modules.

Description of Test Equipment

The combination of the large, custom-made calorimeter and the high-power battery cycler is a one-of-a-kind piece of special purpose test equipment for battery calorimetry. Here, we provide a description and the capabilities of each component.

Calorimeter Description

The calorimeter is of the heat conduction type and is based, in part, on a commercially available isothermal calorimeter (CSC Model 4400 Isothermal Microcalorimeter). Heat-conduction calorimeters sense heat flux between the sample and a heat sink. The heat sink is the enclosure containing the sample and is fabricated with aluminum surrounded by an isothermal bath. If the sample is hotter or colder than the heat sink, heat flows between the heat sink and the sample. In actual practice, the thermal conductivity of the path between the sample and the heat sink is matched to the expected heat flow so that the temperature difference between the sample (the battery, in this case) and the heat sink is minimized. The temperature of the heat sink is kept constant and the entire calorimeter shielded from its surroundings by a constant-temperature bath. The temperature control of the heat sink, together with proper matching of the thermal conductivity of the path between the sample (or measurement cavity) and the heat sink, renders a passive isothermal measurement condition.

The large, custom-made battery calorimeter is pictured in Figure 2 and a block diagram of the calorimeter with a listing of critical components is shown in Figure 3. The measuring unit of the calorimeter includes a 39 cm long, 21 cm wide, and 20 cm high aluminum enclosure connected to a large aluminum heat sink via heat flow sensors (semiconductor thermoelectric devices) that are located between the heat sink and the sample cavity. The bath temperature operating between -30°C to +60°C is controlled with an stability of 0.001°C. For calibration purposes, the measuring unit also incorporates electrical heaters, allowing for heat input at rates of 1 to 80 W. The measuring unit is designed so large-gauge leads, which must be connected to the sample battery for charging and discharging experiments, achieve thermal equilibrium. The large-gauge leads generate a negligible amount of heat even at very large currents. Further, they are attached to the isothermal aluminum enclosure, resulting in an insignificant impact on the accuracy of heat generation data obtained for battery modules. The battery temperature (internal or surface) in the calorimeter is measured with an accurate platinum RTD.

Figure 2. Large Cavity Battery Calorimeter

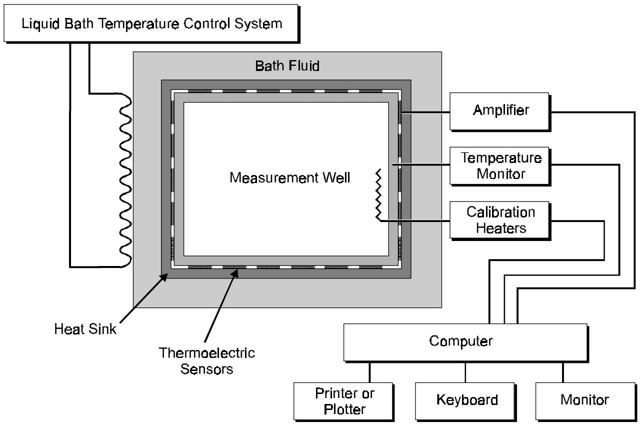

Figure 3. Block Diagram of the Heat Conduction Battery Calorimeter

The measurement cavity can be either dry or filled with a dielectric, inert heat-transfer fluid. The air in the dry chamber can be stirred with small fans and the liquid-filled chamber is stirred with constant-speed stirrers to speed heat transfer from samples to the measurement chamber walls. The small amount of heat added for mixing is taken into account in calculations. The time response of the calorimeter is not affected by stirring within the measurement cavity. However, the time required to reach a steady-state response for a battery at constant power will be shortened significantly by stirring due to improved heat transfer between the sample and the calorimeter. Even under the best circumstances, the time constant for a typical large battery module will be much longer than the response time for the calorimeter.

Battery Cycler Specification

We use a battery cycler (ABC-150 Power System) from AeroVironment of Monrovia, California, to cycle modules in the calorimeter. The cycler is designed specifically for EV and HEV battery testing. It is a fully bidirectional system that supplies power to the batteries for charging and puts a load on the batteries for discharging. The cycler provides voltages from 0 to 445 V and currents of as much as ±530 A. Because the cycler has a rapid response time (maximum response and settling time of less than 50 ms), it can implement multiple commands per second. It can meet the most demanding driving cycle profiles (such as the one shown in Figure 1), including those of the Federal Urban Driving Schedule and the General Dynamic Stress Test (as specified by organizations such as the United States Advanced Battery Consortium). Although the cycler can measure voltage within ±250 mV and current with accuracy of ±200 mA, additional instruments are used to measure voltage and current within accuracies of ±1 mV and ±50 mA when the batteries are cycled with low voltage and currents, respectively.

Results and Discussion

The large, custom battery calorimeter was tested with both internal electrical calibration heaters and with a module simulating a HEV spiral valve-regulated lead acid battery. The simulated battery was constructed from heavy lead foil, fiberglass cloth, and surface-mounted film heaters that were rolled and inserted into an empty Optima Batteries' module containing six cell holders. The simulated module is pictured in Figure 4. The simulated module approximates an actual valve-regulated lead acid battery with respect to thermal mass and thermal conductivity.

Tests were conducted by first achieving steady state conditions at 25°C for the sample, measurement cavity, and the heat sink. Then an exact amount of electrical heat was generated in the measurement cavity. Both the internal heaters and the simulated module were used to collect pulse and steady-state heat rate data. Data obtained from the internal

Figure 4. Simulated Battery Module
(Top photo shows the module case and cover and one of the film heaters used for heat generation; bottom photo shows the "lead/fiberglass/heater rolled" inserts in each cell holder)

heaters are shown in Figure 5; data obtained from the simulated battery are shown in Figure 6. The only obvious difference in the two data sets is the slower response time observed for heat generated with the simulated battery. The time response of the calorimeter without any sample is about 11.5 minute, which is relatively slow because of the size and mass of the measuring cavity for accommodating large modules. This time constant is expected to be shorter than the time constant for full-size battery modules. Because of its large thermal mass, the approximate time response for the simulated module centered in the measurement chamber is 30–45 minutes without any stirring (fans off), which it is expected to be improved to around 15–20 minutes with the air in the measurement chamber stirred.

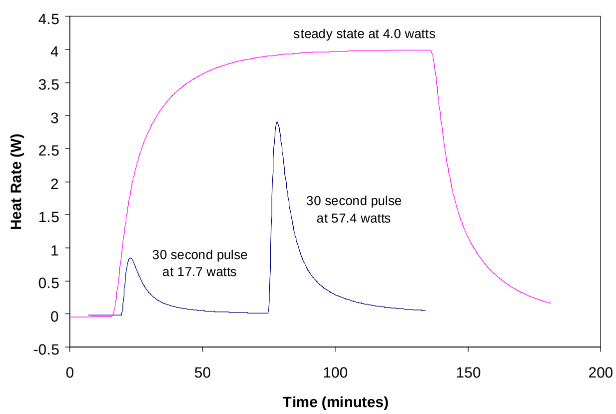

Figure 5. Calorimeter Response Using Internal Calibration Heaters

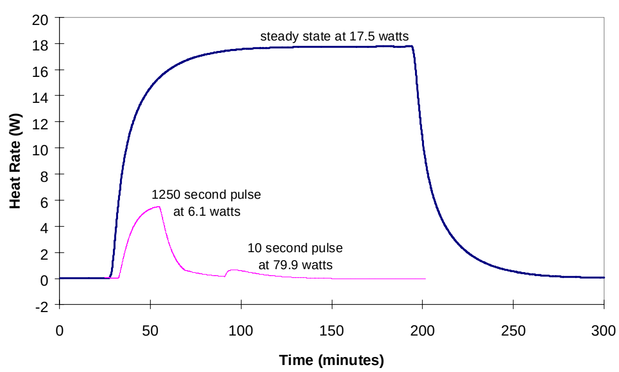

Figure 6. Calorimeter Response Using Simulated Battery Module

Precise measurements of the heater voltage and current as well as the amount of time the heater was on are used to calculate the total heat input to the calorimeter. The shift in the calorimeter output signal and/or the integrated response are used to report the heat rate or integrated heat measured by the calorimeter. Table 1 compares the heat input to measured response for several different experiments using the two different heater systems. The difference between actual heat input and measured heat is less than ± 4.3% for all experiments. The accuracy for future measurements is expected to improve since differences shown in Table 1 are due primarily to poor thermal equilibration of the calorimeter and sample in these experiments. To demonstrate the sensitivity and reproducibility of the calorimeter, we input three very small electric heat pulses each totaling 2.5 J. The calorimeter integrated these three heat pulses with a reproducibility of ± 0.5 J as shown on Figure 7. The baseline stability (noise level) of the calorimeter as shown on Figure 7 is found to be better than ± 1 mW at 25°C.

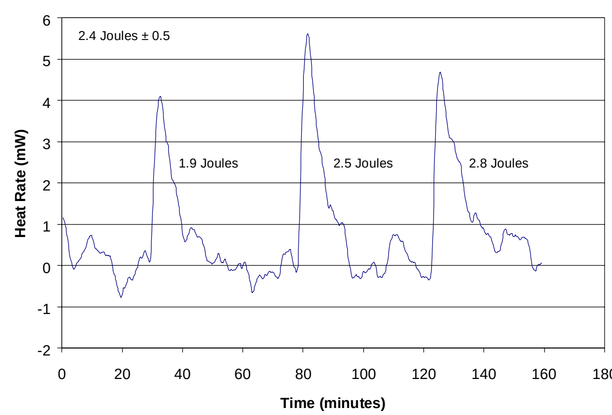

Figure 7. Calorimeter Response to Three Very Small Internal Heater Pulses

Conclusions and Future Work

A new battery calorimeter for obtaining heat generation data from full-size battery modules has been developed and tested. The calorimeter is able to accommodate battery modules with dimensions as large as 21 cm x 39 cm in cross section and as tall as 20 cm. Of course, smaller modules and cells could be tested. The performance data indicated that the calorimeter has a baseline stability of ± 1 mW at 25°C. Tests with a simulated lead-acid HEV module indicated that the calorimeter is able to measure heat effect as small as 10 joules with an accuracy of 5% joule at 25°C. Initial tests indicated that the heat generated from modules could be measured with an accuracy of better than ± 4.3% which is within the specifications for the calorimeter.

The equipment will be used to measure heat generation of lead-acid and other HEV battery modules under test parameters including temperature, state of charge, age, and type of charge/

Table 1. Calorimeter Test Data with Internal Heaters and Simulated Battery Module
(Refer to Figures 5 and 6 for shape of responses.)

Source	Type of Heat Input	Heat Input	Heat Measured	Difference
Internal Heaters	*Pulse*	535 J	546 J	+2.0%
	Pulse	1750 J	1794	+2.5%
	Constant	4.00 W	3.98 W	- 0.50%
Simulated Module	*Pulse*	799 J	765 J	- 4.3%
	Pulse	7625 J	7462 J	- 2.2%
	Constant	17.50 W	17.58 W	+ 0.46%

discharge cycle. Charge/discharge cycles will include constant current and HEV driving cycle profiles. Module energy efficiency will be calculated by testing modules with charge/discharge cycles so the initial and final states of charge are the same. The equipment will also be used to validate thermal and electrochemical battery models developed by the DOE Hybrid Electric Vehicle Propulsion Systems Program participants. Further calorimetry work will focus on obtaining data on small and large modules having different chemistries for use in different applications with the eventual goal of improving their thermal and electrochemical performance.

Acknowledgments

The Department of Energy Office of Advanced Transportation Technologies funded this work as part of a cost-shared HEV program with General Motors, Ford, and Chrysler. We wish to thank Terry Penney, the NREL HEV technology manager, for his support of this project. We would also like to thank representatives from General Motors, Optima Batteries, Bipolar Technologies, and AeroVironment for their technical input and advice. Optima Batteries provided the case and cover and properties data used in fabricating the simulated HEV module.

REFERENCES

1. Pesaran, A.A.; Vlahinos, A.; Burch, S.D.; "Thermal Performance of EV and HEV Battery Modules and Packs," *Proceedings of the 14th International Electric Vehicle Symposium*, Orlando, Florida, December 12-17, 1997.

2. Wipke, K.; Cuddy, M.; Rausen, D.; "Using Systems Modeling to Facilitate the PNGV Technology Selection Process," *Proceedings of DOE Automotive Technology Development Customers' Coordination Meeting*, sponsored by U.S. Department of Energy, Dearborn, MI, October 27-30, 1997.

3. Cohen, R.; Melman, A.; Livne, N., Peled, E.; "Heat Generation in Lithium-Thionyl Chloride and Lithium-SO_2 Cells," *Journal of the Electrochemical Society*, Vol. 139, No. 9, pp. 2386-2391, 1992.

4. Donepudi, V.S.; Conway, B. E.; "Electrochemical Calorimetry of the Zinc and Bromine Electrodes in Zinc-Air Batteries," *Journal of the Electrochemical Society*, Vol. 131, No. 7, pp.1477-1485, 1984.

5. Hansen, L.D.; Frank, H.; "Kinetics and Thermodynamics of Chemical Reactions in Li/$SOCl_2$ Cells," *Journal of the Electrochemical Society*, Vol. 131, No. 1, pp. 1-7, 1987.

6. Sherfey, J.J.; Benner, A.; "Calorimetric Determination of Half-Cell Entropy Changes," *Journal of the Electrochemical Society*, Vol. 105, No. 11, p. 665-672, 1958.

7. Tudron, F. B.; "Dynamic Microcalorimetry: Thermal Effects of Miniature Alkaline Cells Under Load," *Journal of the Electrochemical Society*, Vol. 128, No. 3: pp. 516-520, 1981.

8. Untereker, D.V.; "The Use of a Microcalorimeter for Analysis of Load-Dependent Processes Occurring in a Primary Battery;" *Journal of Electrochemical Society*, Vol. 125, no. 12, pp. 1907-1912, 1978.