Thermal Analysis and Performance of a Battery Pack for a Hybrid Electric Vehicle

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Keywords
"Battery management," "battery model," "thermal management," "HEV (hybrid electric vehicle)," "lead acid," "spiral wound," "finite element calculation," "efficiency."

Abstract
Thermal management of battery packs in hybrid electric vehicles (HEVs) is essential to maximize pack performance and life. In this paper, we will present results of thermal analysis and testing of a battery pack consisting of high-power lead-acid battery modules for the GM/DOE series HEV. Forced air was used as the medium for regulating module temperature the HEV battery pack. A novel air manifold was used to deliver airflow uniformly to each module for even temperature distribution in the pack.

Background
The performance and life-cycle costs of electric vehicles (EV) and hybrid electric vehicles (HEV) depend inherently on energy storage systems such as batteries. Battery pack performance directly affects the all-electric range, power for acceleration, fuel economy, and charge acceptance during energy recovery from regenerative braking. Because the battery pack cost, durability, and life also affect the cost and reliability of the vehicle, any parameter that affects the battery pack must be optimized. Temperature and temperature uniformity have a strong influence on battery pack performance and consequently, that of HEVs and EVs. All the modules in the pack should be operated within the optimum temperature range suitable for the particular electrochemical couple used. In addition, uneven temperature distribution in a pack leads to different charge/discharge behavior that results in unbalanced modules and reduced pack performance [1]. Because HEV batteries have high specific power and undergo aggressive HEV

charging/discharging profiles, thermal issues in an HEV pack are of more concern than in EV packs. For this reason, HEV battery packs require more effective thermal management systems. For proper design of the thermal management system, thermal analysis and tests are required for the modules and packs. This paper presents the results of such efforts for a high-power, lead-acid battery pack for a series HEV.

Introduction

As part of the cost-shared U.S. Department of Energy's and General Motors (GM) Corporation's Hybrid Electric Vehicle Program, GM, Optima Batteries Inc., AeroVironment Inc., and the National Renewable Energy Laboratory (NREL) have been working together to identify and resolve thermal issues associated with a battery pack for a series HEV. The series hybrid test vehicle, developed and tested by GM, contains a Stirling auxiliary power unit and a high-power battery pack consisting of spiral-wound, valve-regulated lead-acid modules [2]. Optima developed and provided the prototype high-power battery modules. AeroVironment integrated and assembled the modules into a pack meeting the requirements of the GM test vehicle. NREL used fundamental heat transfer principles and finite element calculations to predict the temperature distributions in cells, modules, and packs, and provided design input to Optima and AeroVironment on thermal issues. In this paper, we provide non-proprietary information and results of the thermal analysis and testing of modules and the pack.

Vehicles today operate in a wide range of operating temperatures. HEVs of the future would also have to operate in both cold and hot climates. Therefore, performance tests were conducted with the Optima module at various operating temperatures. The performance tests included peak power tests and operating under FUDS 1.0 profiles in HEV operation for various amp-hour (Ah) depletions. FUDS stands for "federal urban driving schedule"; the 1.0 factor indicates its relative power with respect to the standard FUDS. From the FUDS 1.0 profile, the battery efficiency, and charge/discharge resistance were calculated. The tests were performed in an Aerobath®, a temperature-controlled climate device using air circulation. The core battery temperature (measured through a thermal well) was maintained within ±2 °C of the target value throughout the tests. Fig. 1 shows the results of peak power tests for various Ah depletions and temperatures. Fig. 2 shows a similar graph for the battery efficiency as a function Ah depletion at various temperatures under the hybrid FUDS 1.0 cycling. Tests at Optima have indicated that battery capacity loss could occur if the internal module temperature is maintained at above 65°C for a long time (see Fig. 3). Since the efficiency and charge/discharge peak power were better at high temperatures (around 40-50°C) without damaging the modules, the goal of the battery thermal management system was to maintain all the modules in the vehicle around 45°C.

Approach and Discussion

An ideal HEV battery pack thermal management system should maintain optimum operating temperature range for all modules and small temperature variations within the modules and pack. The thermal management system must be compact and lightweight, easily packaged in the vehicle, reliable, and economical. It must also allow easy module access for service and use minimum power for fans and pumps. Based on the GM specified program requirements for the test vehicle, ambient air was selected for thermal control of the battery pack.

To properly design a thermal management system, it was necessary to perform thermal analysis for the modules and the pack as discussed in [1]. In this paper, we first present the results of the thermal analysis for a module, then present the results of thermal analysis for an HEV battery pack along with test results for the same pack.

Module Results

Fig. 4 shows a picture of the latest prototype of Optima modules for HEV applications. It has six spiral-wound lead-acid cells with 16.5 Ah nominal capacity and a nominal voltage of 12 V. Fig. 5 shows a computer model of half of this prototype, which is used for thermal finite element analysis. We assumed that the active core of each cell consists of one homogeneous material with average/effective properties of all of its constituents. We estimated average properties based on the literature and on Optima-generated values. The average heat generation per cell was estimated by AeroVironment and then verified by measurements using NREL's calorimeter [3]. An electrochemical model of the Optima cell, developed by Harb and LaFollette [4], has indicated that the internal local heat generation varies along the length of the cell/module. Using this information, with cooling air flowing upward from the bottom of the module at 2.4 lit/s (5 cfm) and 25°C, we used finite element calculations to obtain the thermal performance for the module. Fig. 6 shows the results of the steady-state temperature distribution in the module, assuming the module is charged-discharged continuously for continuous heat generation. Fig. 7 shows the module wall temperature as a function of longitudinal location. The longitudinal temperature gradient observed is due to the variation in heat generation across the length of the module. We also compared the experimental and analytical core module temperature. Core temperature was measured by inserting a temperature sensor in the thermal well located in the center of one of the center cells. The analysis results agree well (within ± 2°C) with test data.

Pack Results

The goal of the pack thermal management system is to cool the modules during HEV and zero –emission vehicle (ZEV) operation. Secondly, when cooling the pack, the thermal management system should minimize thermal gradients in the pack. Because of the requirement of the test bed vehicle, ambient air was used for cooling the module. This limits module cooling to that of ambient air, which means that cooling the pack at high ambient temperatures is not possible.

The battery pack in the series HEV consisted of 30 (16.5-Ah) Optima modules assembled in two decks of 15 modules (two of the modules were used as service batteries for vehicle starting, ignition, and lighting). The battery pack is about 1.8 m long and it sits in the center of the vehicle between the driver and the front passenger seats. It has two different widths — the narrow section in the front of the vehicle is one module wide, and the wide section in the back seat section is two modules wide. The pack thermal management system consists of a pair of pressurized air plenums that jet air along the sides of each module. A fan at the rear of the pack draws ambient air through the two plenums. In order to provide uniform cooling to each module, it is critical that pressure along the length of the plenum be uniform. Using experiments and with trial and error, we came up with the size of the holes and the shape of each plenum to provide uniform flow rate to each module even in the area of transition from narrow section to wide section while maintaining a low airflow path resistance. The bench top tests (presented in Fig. 8) indicated that the new air flow path design resulted in air flow uniformity of ± 7.5% which was much better than the best previous design with flow uniformity of ± 25%. These design recommendations were implemented in the latest battery pack assembly and installed in the GM/DOE test vehicle.

Several battery packs with the described thermal management system were fabricated and tested. To simplify discussion of the thermal performance test results, the pack is broken down into four subsections: upper single-wide, upper double-wide, lower single-wide, and lower double-wide. This corresponds to the upper and lower decks and the sections that are one and two modules wide. The subsections are shown in Fig. 9. The goals of the thermal tests were to determine steady-state operating temperature of the pack during HEV operation, the heat transfer rate during HEV operation, pack thermal gradients during HEV operation, and module warm up time during ZEV operation. HEV cycling was done using AeroVironment's ABC-150 Battery Cycler using FUDS 1.0 and FUDS 1.3 profiles with a specified auxiliary power unit strategy. During all tests in which the pack was out of the vehicle, the pack was cycled with a thermal blanket to simulate the insulation of the battery box in the vehicle. This was to prevent radiation losses that do not exist when the pack is not in the vehicle. When the fan was on full power, it provided 66 lit/s (140 cfm) to the pack. Ambient temperature in the lab was 22ºC -23ºC during all the tests.

The first thermal tests were done on a hybrid FUDS 1.0 (HFUDS) with the fan on 100%. The purpose of this test was to determine the steady-state pack operating temperature. Measured core temperatures for modules were used to estimate subsection average temperatures. The average pack temperature started at 23ºC and increased to 32ºC in approximately 1.25 hours (3.5 HFUDS cycles) as seen in Fig. 10. The average module temperature variation from subsection to subsection is 1°C or less during sustained HEV operation and the difference from absolute minimum to maximum module temperature is 2°C. Note that the temperature sensors used have a resolution of 1°C. Fig. 10 also shows the thermal model results for the core temperature assuming constant heat generation and uniform air flow distribution. Note that in the thermal model, all the modules were assumed to be exposed to the same boundary conditions (airflow rate and inlet temperature) and generated heat at the same rate so the average pack temperature was the same as the module temperature.

The second thermal test observed the module temperature during hybrid FUDS 1.0 cycling with the fan being turned off or on via a control feedback loop with an operating set point of 45ºC based on the average module temperature. During cycling the modules warmed up to 45ºC in 3.25 hours (9 HFUDS cycles) with the average module temperature difference from subsection to subsection being 2°C or less. The fan was easily able to keep up with the heat load of approximately 280W generated during HEV operation and maintained the pack at 45ºC by cycling on and off. The pack temperature during operation can be seen in Fig. 11 along with the thermal model results using uniform airflow distribution and constant heat generation.

The third thermal test was performed under hybrid FUDS 1.3 operation. As with the hybrid FUDS 1.0 tests, the fan was controlled using the control feedback loop with an operation set point of 45ºC. The module temperature rose to 45ºC in approximately 45 minutes (2.5 cycles), with the average module temperature from section to section being less than 1ºC (as shown in Fig. 12.). Unlike the hybrid FUDS 1.0 tests, the fan was unable to keep up with the heat load of the pack. The heat generation during hybrid FUDS 1.3 cycling was approximately 920W, significantly (330%) greater than the 280W generated during hybrid FUDS 1.0 cycling. The average pack temperature reached a steady-state value of approximately 47.5ºC slightly higher than the operation set point. This indicated that a higher airflow rate and thus a more powerful fan or a lower pressure-drop flow path was needed. The average module temperature differences from subsection to subsection (once the fan is operating) were less than 1°C except for the upper single-wide subsection, which was running about 2°C higher than the other subsections. The difference between the absolute minimum and maximum was about 8°C, which showed that there is a need for improvement in airflow distribution to each module. Fig. 12 also shows the results of the thermal model using constant heat generation and uniform airflow distribution.

Conclusions

HEV battery packs require thermal management systems to regulate module temperatures evenly within the desired operating range. To properly design a thermal management system, it is necessary to perform thermal analysis and tests for the modules and the pack. To design and fabricate the pack thermal management system for the high power battery pack of the GM/DOE series HEV we conducted thermal analysis and testing. The pack thermal management system performed as designed. It cooled the modules in a uniform manner with the exception of the high thermal load of the hybrid FUDS 1.3 operation; this resulted from the unavailability of a higher airflow rate from the selected fan because of larger than expected resistance in the airflow path. Although the system performs very well during hybrid FUDS 1.0, there is need for improvement on hybrid FUDS 1.3 operation by using a more powerful fan. Furthermore, it took a considerable length of time (1-2 hrs) for the modules to warm up to the desired temperature range in hybrid operation. The current thermal management system needs to be modified to (1) add heat to the system for optimum operation in cold climates or (2) remove heat using active cooling — such as refrigeration — in very hot climates (ambient conditions greater than 45°C), which is necessary to bring the modules to optimum operating temperature.

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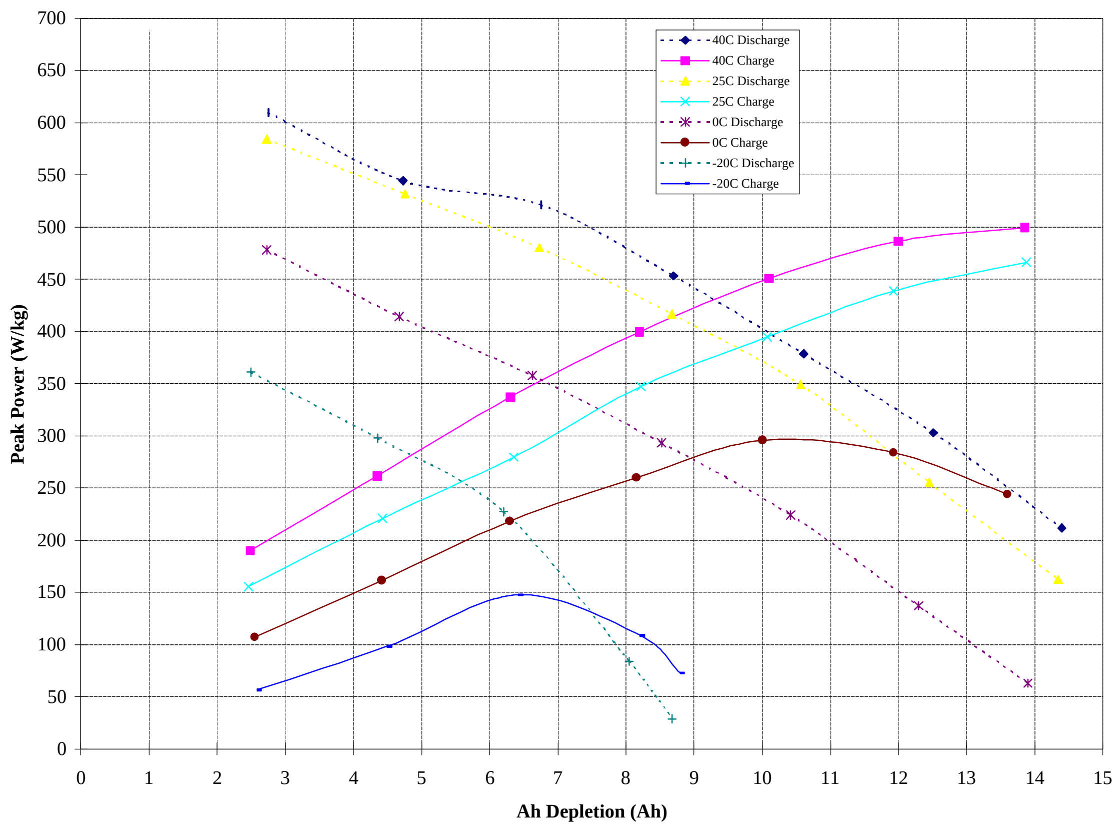

Fig. 1: Results of peak power tests for Optima HEV modules at different temperatures

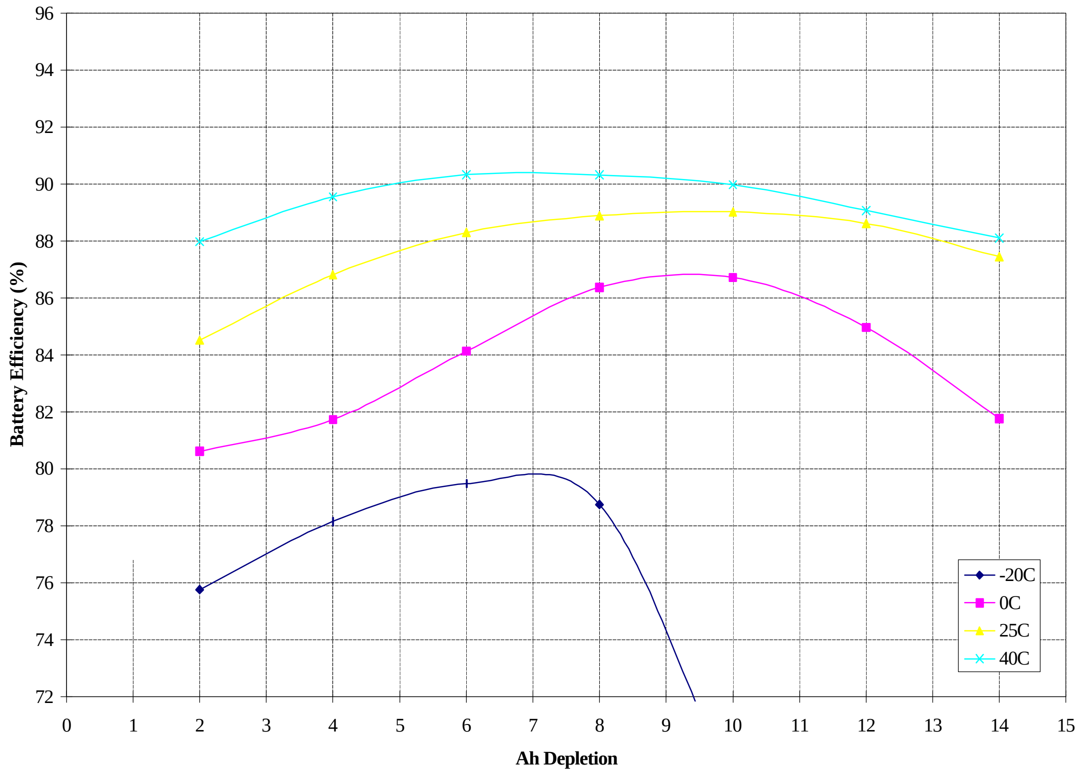

Fig. 2: Battery efficiency for Optima HEV modules at different temperatures under hybrid FUDS 1.0 cycle

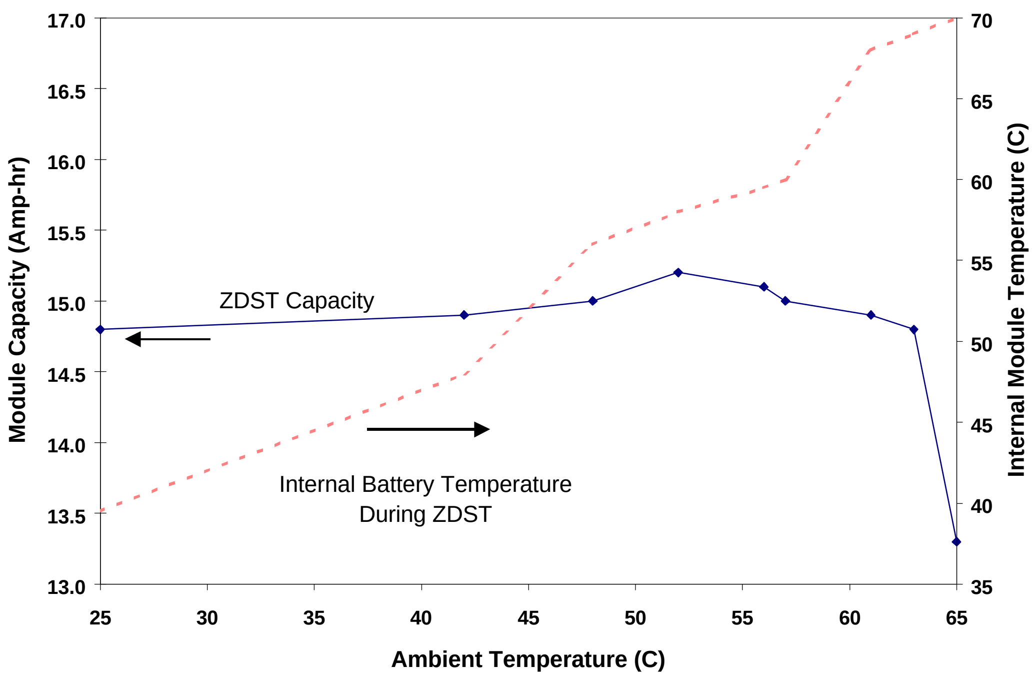

Fig. 3: Capacity of Optima HEV modules as a function of temperature during ZDST (All-electric Dynamic Stress Test)

Fig. 4: Photos of new generation of Optima HEV prototype modules

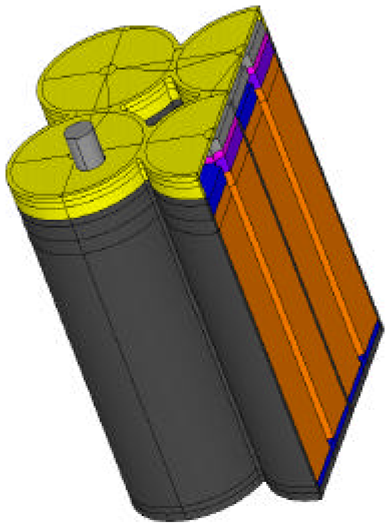

Fig. 5: Computer-generated solid model of an Optima HEV module

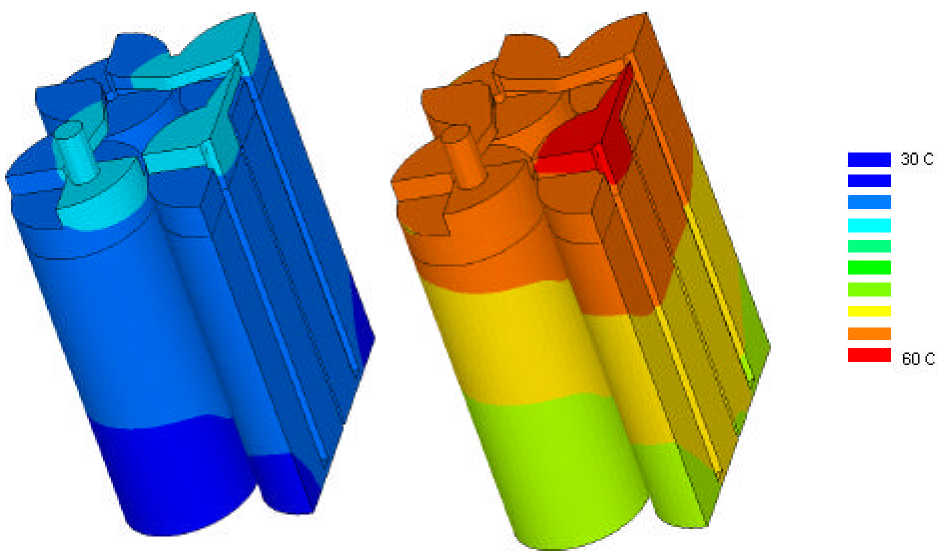

Fig. 6: 3-D steady-state temperature distribution in Optima HEV modules (left figure is for FUDS 1.0 with average heat generation of 10 W/module; right figure is for FUDS 1.3 with average heat generation of 32.9 W/module). Note that each color range is about 3.3°C.

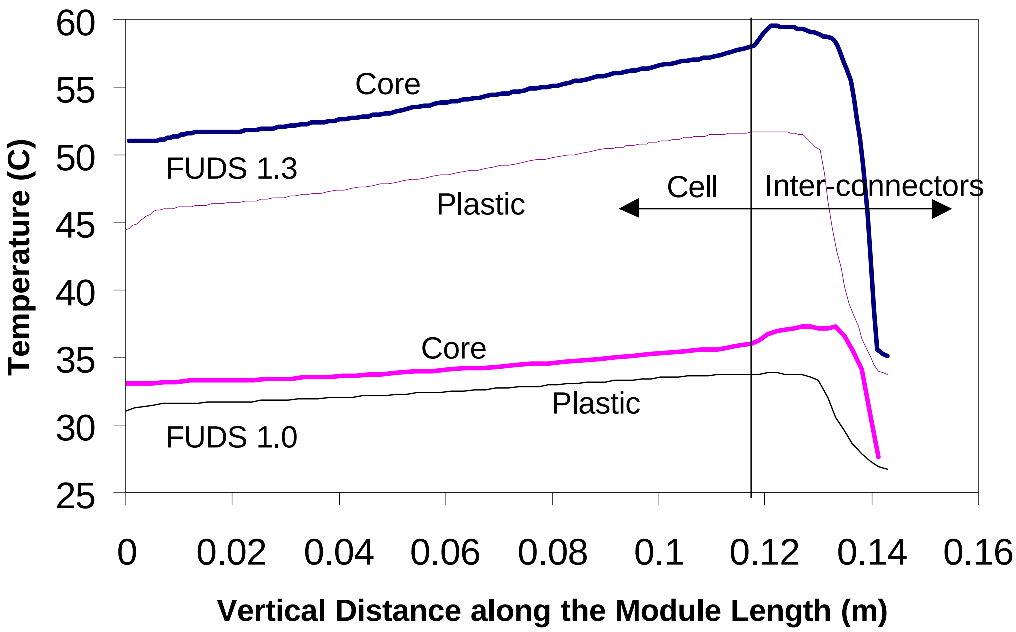

Fig. 7: Steady-state thermal model results for Optima HEV modules along the centerline (with constant heat generation for FUDS 1.0 and FUDS 1.3)

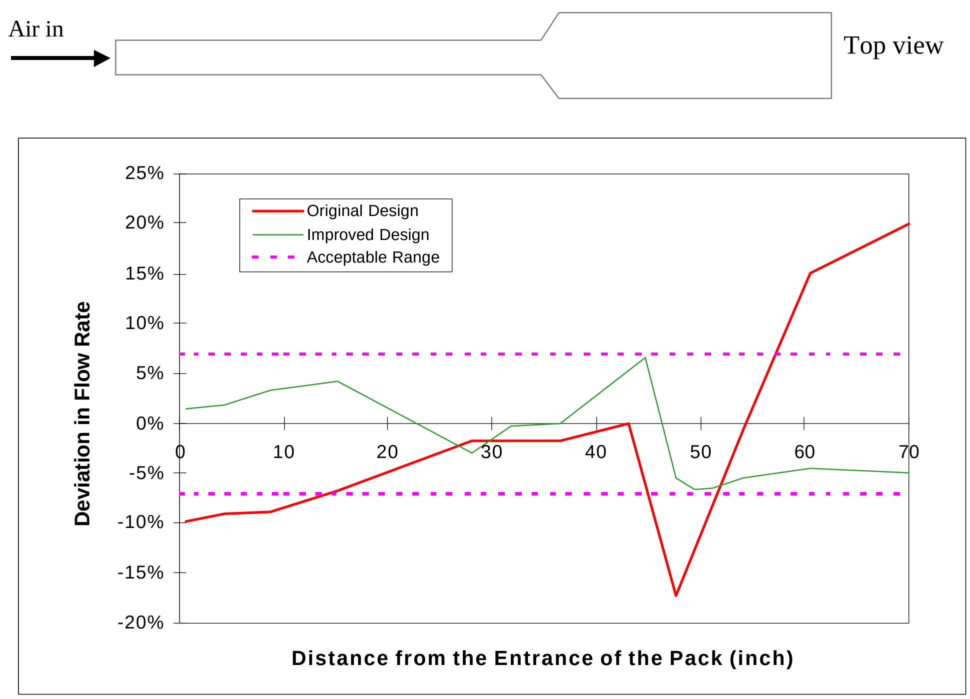

Fig. 8: Improving battery pack flow uniformity by modifying flow path design

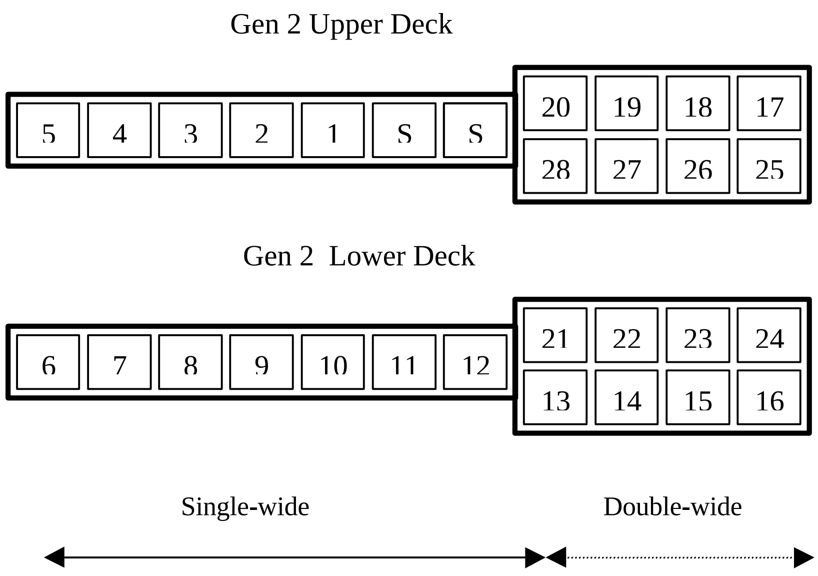

Fig. 9: Top view of battery pack layout (service batteries are designated as S)

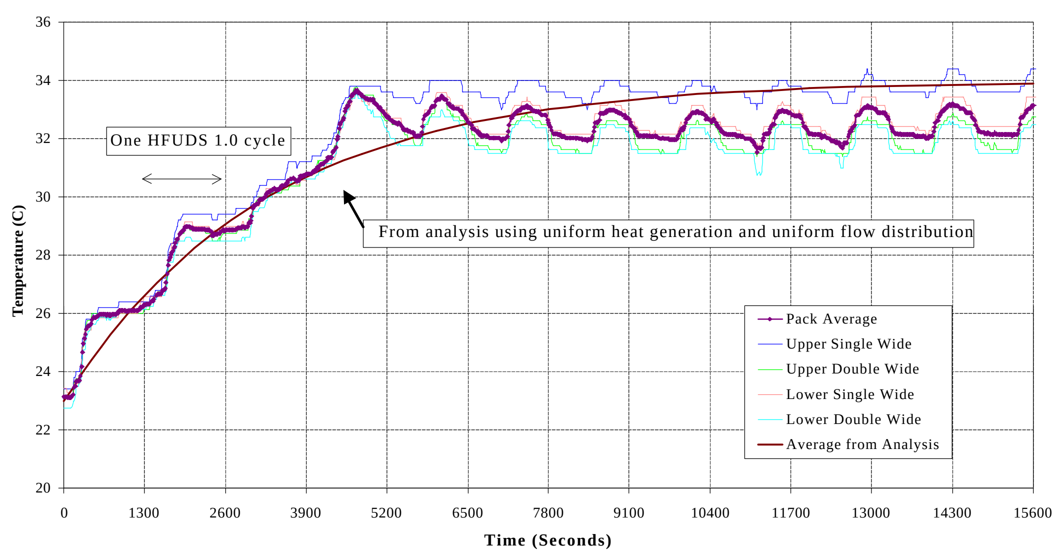

Fig. 10: Battery pack thermal performance under hybrid FUDS 1.0 cycling with fan on

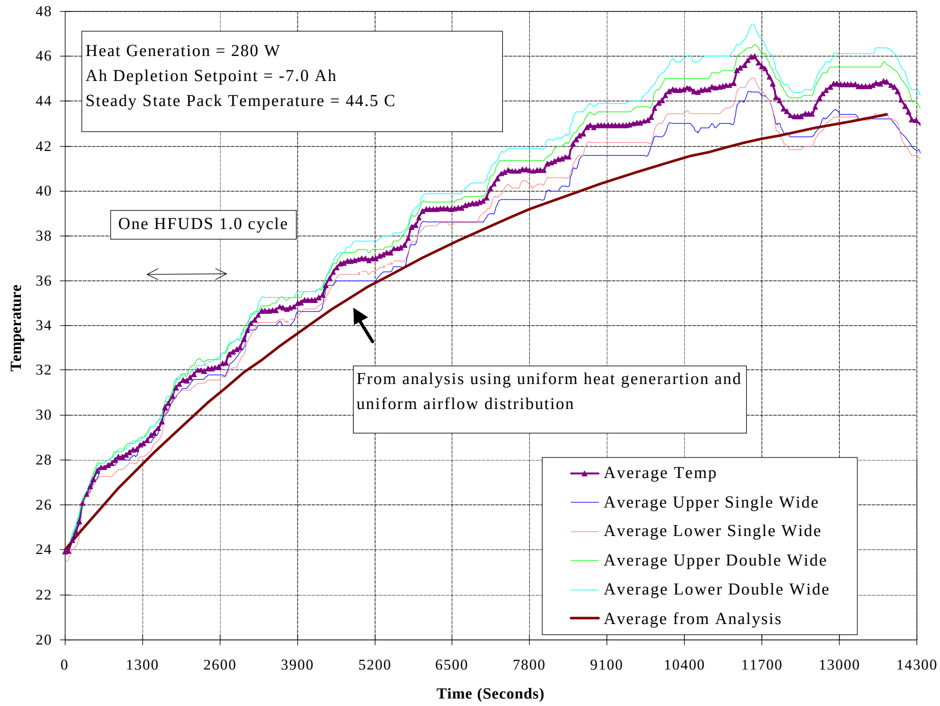

Fig. 11: Battery pack thermal performance under hybrid FUDS 1.0 cycling with fan on/off strategy

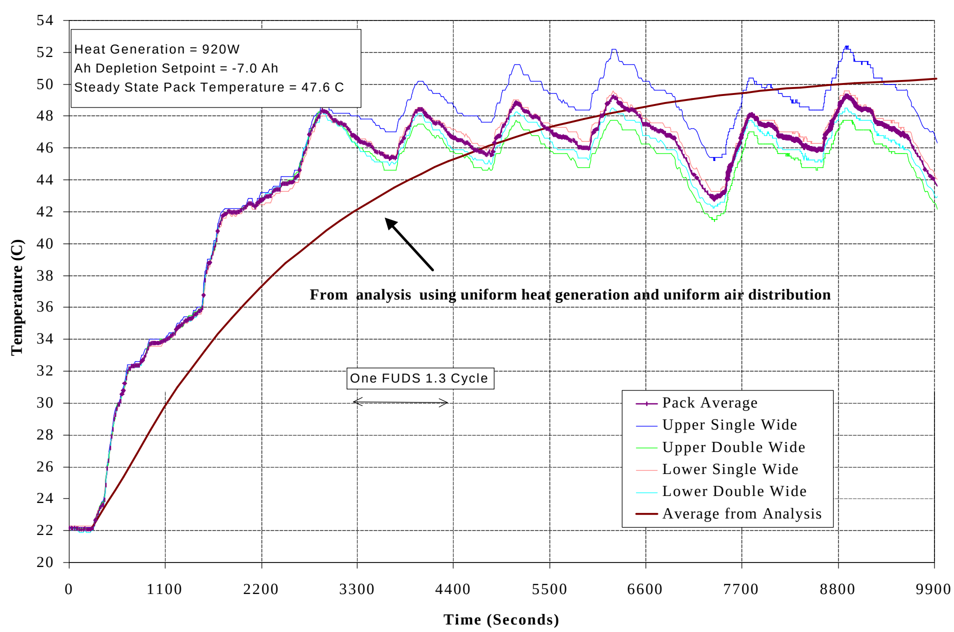

Fig. 12: Battery pack thermal performance under hybrid FUDS 1.3 cycling with fan on/off strategy