

Design of Direct and Indirect Liquid Cooling Systems for High-Capacity, High-Power Lithium-Ion Battery Packs

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ABSTRACT

Battery packs for plug-in hybrid electrical vehicle (PHEV) applications can be characterized as high-capacity and high-power packs. For PHEV battery packs, their power and electrical-energy capacities are determined by the range of the electrical-energy-driven operation and the required vehicle drive power. PHEV packs often employ high-power lithium-ion (Li-ion) pouch cells with large cell capacity in order to achieve high packing efficiency. Lithium-ion battery packs for PHEV applications generally have a 96SnP configuration, where S is for cells in series, P is for cells in parallel, and $n = 1, 2$ or 3 . Two PHEV battery packs with 355V nominal voltage and 25-kWh nominal energy capacity are studied. The first pack is assembled with 96 70Ah high-power Li-ion pouch cells in 96S1P configuration. The second pack is assembled with 192 35Ah high-power Li-ion pouch cells in 96S2P configuration. The battery temperatures are managed with a direct liquid cooling system for the 96S1P pack and with an indirect liquid cooling system for the 96S2P pack. Procedures are discussed for the cooling system design for both direct liquid cooling and indirect liquid cooling packs. A design criterion is proposed for obtaining a uniform coolant flow distribution in the battery pack. Thermal behavior of the cells in both battery packs are simulated using 3D finite element models under 4C continuous discharge from a fully charged state to 90% depth of discharge, simulating the worst condition for the PHEV battery pack utilization.

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INTRODUCTION

Plug-in hybrid electrical vehicles have two operation modes: (1) electrical-vehicle (EV) or charge-depleting (CD) mode and (2) hybrid-electric-vehicle (HEV) or charge-sustaining (CS) mode. For PHEV battery packs, their electrical-energy and power capacities are determined by the EV mode range and the required vehicle drive power. Battery packs for PHEV applications may be characterized as high-capacity and high-power packs. During EV mode operations, the state of charge (SOC) of the battery cells typically drops from 90% to 25% (i.e., the usable capacity $\Delta\text{SOC} = 65\%$). The battery pack for PHEV applications operates at its full energy and power capabilities during EV mode with high discharge/regen pulse currents, resulting in considerable heat generation in the battery cells at the end of EV mode. The maximum cell temperature and the maximum differential cell temperature are commonly encountered at the end of the EV mode.

Design of the thermal management system for a PHEV battery pack generally starts with the following specifications: (1) the pack electrical energy capacity and power requirements; (2) the pack configuration; (3) the heat

rejections of the battery cells in the pack under the target cell utilizations; (4) the allowable maximum cell temperature and the maximum differential cell temperature for cell utilizations. Based on these specifications, the pack design and the thermal management system can be determined. In a battery pack, the cells are assembled in groups or modules. The cells in each of the modules are connected in a certain series-parallel configuration to achieve the required capacity and voltage. Resulting modules are connected in series to meet the required pack voltage. In an ideal thermal management system of a battery pack, all the modules within the pack would be identical and would have the same cooling condition. Computational fluid dynamic (CFD) may be used to ensure uniform flow distribution to the various battery modules within the battery pack. Hence from the thermal management point of view, the battery module is the basic unit for the battery pack. Based on coolant flow analysis, the appropriate heat transfer boundary conditions for the battery module can be defined. The temperature distributions of the cells within the battery module under the various utilizations and cooling conditions provide sufficient insights to the thermal behavior of the cells within the battery pack. A good

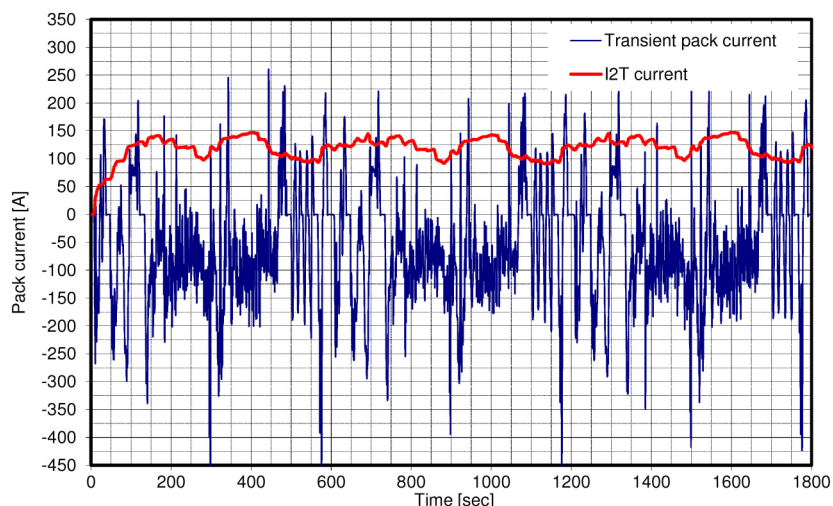


Figure 1. Selected simulations of e-motor activities for the EV mode operation under a user specified cycle.

thermal management of a battery pack starts with the proper selection of the battery cell, a good understanding of the thermal behavior of the cell, and good electrical and thermal designs of the module. Besides the maximum cell temperature and the maximum differential cell temperature, the maximum cell-to-cell temperature difference in the pack also must be controlled in the battery thermal management. The pack power capability is affected significantly by temperatures of the cells in the pack. In low-temperature operations the coolest cell determines the pack power capability. When operated at elevated temperatures, the hottest cell within the pack limits the pack power. The maximum cell-to-cell temperature difference in the pack is governed by the cooling medium flow distribution among all the cooling units of the pack. Thermal modeling of the cells and modules as well as the cooling medium flow distribution in the pack can play an important role in the early stage of the pack development to ensure that the battery pack performs properly under specified duties. In the following sections, the design of the battery thermal management system for a high-capacity and high-power Li-ion pack for PHEV applications will be discussed.

BATTERY SYSTEM DESCRIPTION

Target Performance of Battery Pack

The PHEV under consideration is for a light-duty truck application. The electric power requirements for the PHEV battery pack are presented in Table 1. It is assumed that the e-motor of the vehicle will be operated around 350V and the target pack-useable-energy capacity is 16 kWh. By assuming $\Delta\text{SOC} = 65\%$ for the EV mode operations, e.g., SOC of the battery cells drops from 90% to 25%, the nominal energy capacity of the pack is 25 kWh. The battery pack currents based on the simulated e-motor activities for the EV mode operation under a user specified cycle are shown in Figure 1. The positive and negative currents indicate the e-motor at the

regeneration mode (charging battery) and drive mode (battery discharge) respectively.

Table 1. Battery pack electric power requirements at 25 °C.

Discharge power (2s)	200 kW
Discharge power (10s)	175 kW
Charge power (2s)	150 kW
Charge power (10s)	100 kW

Pack Configuration and Cooling Method Determination

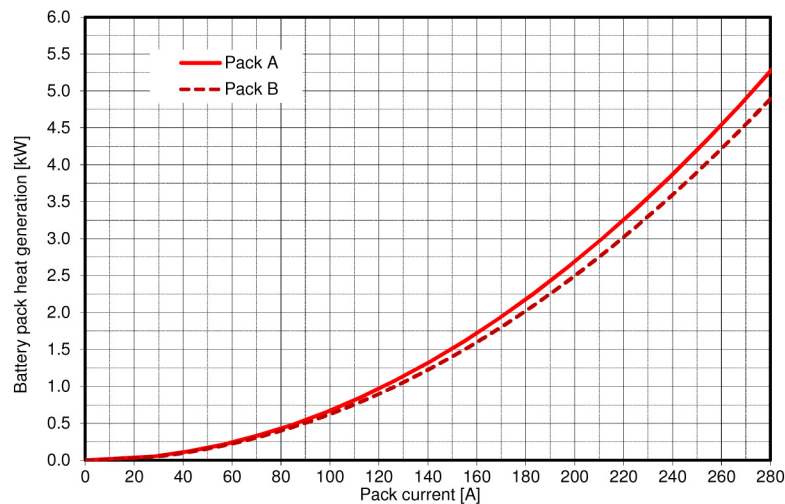
PHEV packs often employ high-capacity and high-power Li-ion pouch cells in order to achieve high packing efficiency. Two high-capacity and high-power Li-ion pouch cells are selected for this studies. The cell specifications are given in Table 2. To meet the required pack voltage and energy capacity, 96 Cell A are connected in 96S1P configuration and 192 Cell B are connected in 96S2P configuration. For simplicity, the 96S1P pack and 96S2P pack are referred to as Pack A and Pack B respectively. Both packs have 355V for the pack voltage and 25 kWh for the pack energy capacity.

Cooling must be provided to every single cell in the pack; hence cell cooling design starts with characterizations of the battery cell heat generations. Like other electrical systems, a battery system can tolerate a short duration of electrical overloading. In this study, the battery thermal load is evaluated with an $I^2\tau$ current defined as

$$I_{\tau} = \sqrt{(\int_{\tau} i^2 dt) / \tau} \quad (1)$$

Table 2. Specifications of high-capacity and high-power Li-ion pouch cells.

Items	Cell A	Cell B
Nominal capacity	70 Ah	35 Ah
Nominal voltage	3.7 V	3.7 V
Internal resistance	< 0.7 mΩ	< 1.3 mΩ
Max continuous charge rate	3C	3C
Max continuous discharge rate	6C	8C
Peak discharge rate	10C	12C
Operation temperatures	-15 to 60 °C	-15 to 60 °C
Mass	1450 gram	880 gram
Thickness × Width × Height	11 mm × 248 mm × 260 mm	9 mm × 210 mm × 220 mm

**Figure 2. Battery pack heat generations as a function of pack discharge current for Pack A and Pack B.**

where I_τ is a root-mean-square (rms) average current over a window time τ (i.e., the I_τ^2 current) and i is the transient current. Because τ is a moving window, $I_\tau = I_\tau(t)$ is a transient current in a thermal load sense, with the thermal history up to τ being considered. The window time τ is taken as 120 seconds in this study. I_τ^2 currents corresponding to the dynamic pack currents in the user specified cycle are also presented in Figure 1. As is seen in Figure 1, the maximum value for I_τ^2 currents is only 140A, equivalent to a continuous discharge at 2C rate for the cells in both Pack A and Pack B. For a PHEV, the cases of a short duration of continuous discharge may be encountered and the corresponding cell heat generations may be greater than those due to dynamic loading in the specified drive cycle. Due to the asymmetric charge-discharge performances of the two candidate cells, this continuous discharge is limited to 4C rate in this study. Figure 2 shows the total battery heat generations for Pack A and Pack B with the pack current up to 280A (equivalent to 4C discharge rate). The corresponding heat generations for Cell A and Cell B are presented in Figure 3. Although the two packs have similar total battery heat generations, heat generations at the cell level differ significantly. At 280A pack

current, the cell heat generations are 55.5 W/cell for Cell A and 25.8 W/cell for Cell B.

The battery cooling method is determined at the cell level because the maximum cell temperature ($T_{\text{cell,max}}$) and the maximum differential cell temperature ($\Delta T_{\text{cell,max}}$) for every single cell in the pack must meet the criteria for the battery cooling system design. For high-capacity and high-power Li-ion pouch cells, the criteria for the battery cooling system design are often set as $T_{\text{cell,max}} \leq 55^\circ\text{C}$ and $\Delta T_{\text{cell,max}} < 8^\circ\text{C}$. The low heat capacity and heat transfer coefficient (HTC) of air limit the capability of air cooling; air cooling is generally applicable to battery systems with low cell heat rejections (< 10 W/cell) [1,2]. Because of the high cell heat generations, the cells in both Pack A and Pack B must be cooled with liquid either directly or indirectly. Discussions of various cooling systems have been given in references [3,4]. Liquid is a secondary coolant and itself must be cooled with ambient air through a coolant radiator. Under high ambient temperatures, the coolant temperature out of the radiator may exceed the limiting coolant temperatures at the pack inlet. Thus, a liquid cooling system for the battery pack is generally integrated with the AC system of the vehicle through a

refrigerant cooled chiller to deal with the cases when the coolant radiator is not capable of bring the coolant temperature down to the required pack inlet temperature [2].

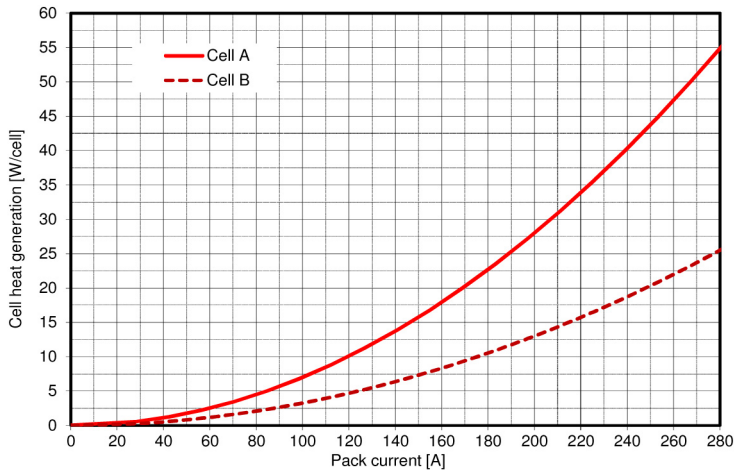


Figure 3. Cell heat generations as a function of pack discharge current for Cell A and Cell B.

CHARACTERISTICS OF DIFFERENT LIQUID COOLING SYSTEMS

High-power pouch cells are often cooled through a thin aluminum heat sink plate or cooling fin in contact with one surface of each cell in the pack. In a direct liquid cooling system, the cell is cooled with coolant flowing through the coolant passages of the heat sink plate which is in direct contact with the cell. In an indirect liquid cooling system, each of the heat sink plates has an extended surface that is in contact with a cold plate cooled with coolant flowing through it. These two liquid cooling systems will be discussed in the following subsections.

Direct Liquid Cooling System

A direct liquid cooling system has high cooling capability and high compactness. In such a cooling system, a basic cooling unit is formed by two cells with an aluminum heat sink plate inserted between them. The cells are cooled by the coolant flowing through the coolant passages in the heat sink plate. The side surfaces of the cells that are not in contact with the heat sink plate are thermally insulated from the adjacent cells by an elastomeric thermal pad as shown in Figure 4. The coolant passages in the heat sink plate can be designed according to the cell heat flux distribution, i.e., through the coolant passage design and coolant flow control in each of the coolant passages, precision battery cooling can be achieved theoretically. Figure 5 shows some examples of heat sink coolant passage designs reported in the literature [5,6,7]. In direct liquid cooling, the coolant flows to all the heat sink plates or cooling channels are in parallel. There are 48 cooling channels for a pack with 96 cells (Pack A in this study). All the cooling channels in the pack are integrated

through the coolant supply and collection plenums or manifolds, forming the coolant-flow system for the pack. Distribution of coolant flows among the 48 cooling channels in the pack governs the maximum cell-to-cell temperature difference in the pack. It is a great challenge to design a direct liquid cooling system with the coolant flows evenly distributed in the 48 cooling channels. Sealing of 48 cooling channels and connectors is another challenge in the cooling system design. In addition, each of the cooling channels has multiple coolant passages (Figure 5). A big disadvantage of the direct liquid cooling system is its complexity. Coolant leaks in any of the many connections to the 48 cooling channels and the multiple coolant passages within each of the cooling channels may cause the entire cooling system to fail.

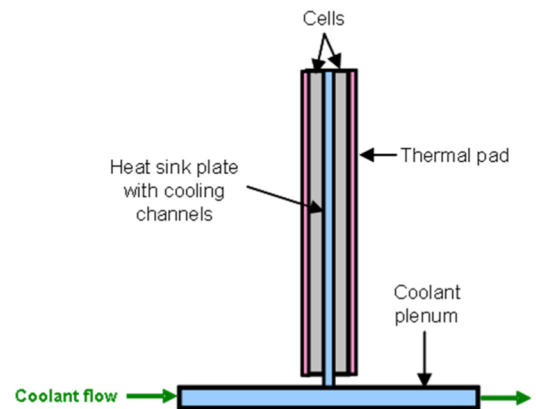


Figure 4. Illustration of a cooling unit for direct liquid cooling.

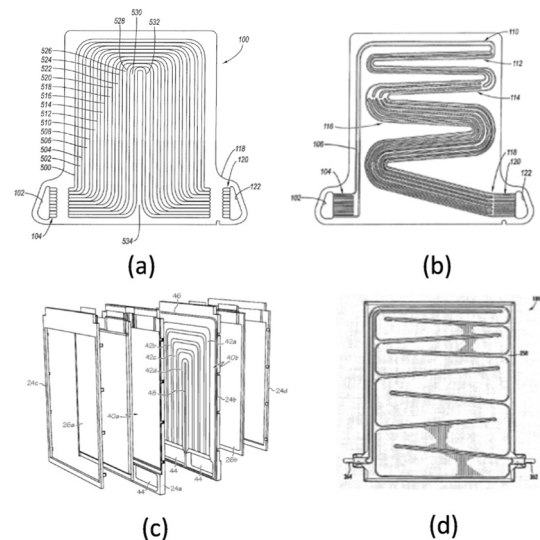


Figure 5. Examples of heat sink coolant passage designs: (a) and (b) - GM; (c) - Delphi; (d) - LG.

Indirect Liquid Cooling System

A basic cooling unit in an indirect liquid cooling system is shown in Figure 6. Each pair of cells in the pack is cooled