Journal of Power Sources 267 (2014) 784–792

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Simulative method for determining the optimal operating conditions for a cooling plate for lithium-ion battery cell modules

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HIGHLIGHTS

- A method to optimize operating conditions for multiple objectives is presented.
- The method is demonstrated on a cooling plate for an electric vehicle battery.
- The method can be generalized to any battery thermal management system.
- The appropriate simulation model for the analyzed case is discussed.
- The results enhance the effectiveness of dynamic one-dimensional simulations.

ARTICLE INFO

Article history:
Received 17 February 2014
Received in revised form
26 May 2014
Accepted 1 June 2014
Available online 10 June 2014

Keywords:
Lithium-ion
CFD
Thermal management
Electric vehicle
Cooling plate

ABSTRACT

Extended battery system lifetime and reduced costs are essential to the success of electric vehicles. An effective thermal management strategy is one method of enhancing system lifetime increasing vehicle range. Vehicle-typical space restrictions favor the minimization of battery thermal management system (BTMS) size and weight, making their production and subsequent vehicle integration extremely difficult and complex. Due to these space requirements, a cooling plate as part of a water–glycerol cooling circuit is commonly implemented.

This paper presents a computational fluid dynamics (CFD) model and multi-objective analysis technique for determining the thermal effect of coolant flow rate and inlet temperature in a cooling plate—at a range of vehicle operating conditions—on a battery system, thereby providing a dynamic input for one-dimensional models. Traditionally, one-dimensional vehicular thermal management system models assume a static heat input from components such as a battery system: as a result, the components are designed for a set coolant input (flow rate and inlet temperature). Such a design method is insufficient for dynamic thermal management models and control strategies, thereby compromising system efficiency. The presented approach allows for optimal BMTS design and integration in the vehicular coolant circuit.

1. Background and motivation

Electric vehicles rely on high capacity and energy density power storage systems to extend the vehicle range and mass-market appeal. Currently, automobile manufacturers implement various Lithium-ion battery cells because they offer high power densities and are commercially available. The cells are high in cost [1] making a maximization of their lifetime desirable, which differentiates them from consumer cells found in small electronics such as laptops. Lithium-ion cells age not only over time, but also due to other influences including their state of charge (SOC), charging or discharging rate (C-rate), the depth of discharge (DOD), and extreme temperatures [2]. All these factors have varied effects on the multitude of cell chemistries in use today, but it is clear that temperature has a universal influence on the performance degradation of nearly all positive electrode and electrolyte chemistries [3]. High-current cycling, which is required for high performance and rapid-charging applications, significantly increases the temperature in the cell [1]. According to Bandhauer et al. [3] heat produced in a cell stems from three fundamental sources: activation interfacial kinetics, concentration species transport, and ohmic Joule heating

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http://dx.doi.org/10.1016/j.jpowsour.2014.06.001
0378-7753/

from the movement of charged particles losses, which becomes very significant for larger cell sizes such as those discussed in this paper. The goal of a BTMS is to increase the lifetime of Lithium-ion cells by regulating the temperature influences on the cell. A BTMS is especially effective when cells are susceptible to high rates of charging (e.g. rapid charging or regenerative breaking) and discharging (e.g. high performance vehicles, plug-in hybrids) and when the vehicle is operated in very high or low ambient temperatures.

Maintaining temperatures between approximately 25 and 35 °C while achieving a uniform temperature across each cell and across cell packs (so called modules) helps limit aging [4]. Pesaran et al. [4] have shown on the example of a pouch cell that large temperature gradients over a single cell reduces its lifetime. Premature aging of a single cell degrades the performance of a module noticeably because of the circuitry between the cells: when connected in series, the weakest cell will influence the maximum capacity of the system.

Thermal management itself is not the primary challenge, but rather the extremely restricted space available to a BTMS in a modern vehicle. All battery system components including the BTMS must vie for space with the multitude of components in a modern luxury vehicle. Since millimeter increases in the dimensions of the BTMS cannot be tolerated, it is critical to optimize the potential of the BTMS while minimizing the occupied area.

In the case of an active thermal management system, the ideal working fluid is already present in the vehicle (e.g. air, antifreeze or refrigerant) and available within the desired temperature range. The amount of additional components required for the BMTS are thereby reduced, effectively lowering the size, weight, and ultimately the cost of the system. For example many production hybrid-electric vehicles (HEV) use forced air for cooling and heating, taking advantage of existing technologies within the vehicle; however, battery systems in plug-in hybrid vehicles (PHEV) often have greater thermal management requirements because they operate under high charge and discharge rates.

In the case of a PHEV liquid cooling is advantageous, especially considering that the system is generally integrated into a vehicle with an internal combustion engine, leaving even less space for the BTMS [5]. Some sort of cooling plate is implemented in most currently available plug-in hybrid electric (PHEV) vehicles and mentioned in numerous patents from major vehicle and cooling system manufacturers [6–10] and is therefore the focus of this paper. Cooling from the small surface at the bottom of a prismatic cell is thermodynamically suboptimal; however, there are numerous other factors that have made cooling plates prominent such as the minimal space requirements in the vehicle, the availability of components from predominant cooling system manufactures, and the ability of the cooling plate to provide structural support to the battery and integrate into a so-called battery module (see Section 4).

The quantities of interest for evaluating the performance of the cooling plate are the (1) temperature differences over individual cells, (2) amongst the cells (i.e. within a module), (3) the maximum cell temperature, and the (4) coolant pressure loss through the plate. The maximum temperature and temperature difference over an individual cell must be minimized in order to slow aging of the cell; the temperature differences over individual cells in a module must be similar in order to avoid inhomogeneous aging amongst the cells and subsequent capacity reduction due to the failure of a single cell electrically connected in series with others. The maximum temperature must also be controlled to ensure safe operation. The pressure loss influence the pump size required, which influences energy consumption and vehicle integration by requiring mechanically stronger cooling plates to withstand the higher pressure forces, leading to higher costs. These costs must be justified by an improvement in the performance of the cooling plate resulting in an increased cell-lifetime.

This paper presents a simulative method using commercially available computational fluid dynamics (CFD) software to predict the optimal cooling circuit operating conditions (coolant volumetric flow rate and inlet temperature) for a variety of vehicle operating conditions (ambient temperature, vehicle speed and SOC) in order to minimize the pressure loss across the BTMS, the temperature gradients over and amongst the cells, and the maximum cells temperatures. The analysis is performed on a battery module developed in the research project *eProduction* (presented in Section 2.3). Various simulative models for the module are first compared in order to find the most efficient yet accurate cell model.

The goal of this method is to provide BTMS designers with universal results (i.e. not flow channel geometry specific) to assist in designing cooling systems economically for optimal vehicle integration while extending cell life-time and vehicle range. These results also extend the effectiveness of vehicular one-dimensional thermal management system models because the thermal state of the battery is calculated over the complete range of coolant flow rates and inlet temperatures, making dynamic feedback control possible and greatly enhancing the efficiency of the vehicle's thermal management system.

2. Design considerations for battery modules and a CFD-Model

2.1. Energy consumption of the BTMS

Currently available electric vehicles from the Tesla Model S to the Nissan Leaf consume approximately 0.187 kWh km^{-1} according to the manufacturer's specifications. Based on this data, the effect of pump size alone on vehicle range at different average speeds is calculated and shown in Table 1.

Losses to cooling system pumps clearly become more significant at lower speeds, when the electric motor consumes less power, yet the pump remains on. Table 1 further illustrates the benefit of dynamic thermal system control, as the total pump power is most likely not required continuously. The simulative method presented in this paper identifies the required pump power at various operating points, providing the necessary input for a one-dimensional vehicle thermal system model.

2.2. The cell: heat source for the CFD model

This analysis considers the prismatic SANYO/PANASONIC PHEV-2, 25 Ah Lithium-ion cell, which was developed for the

Table 1
Energy consumption of coolant circuit pump as percent of total energy consumption at various vehicle speeds.

Vehicle average speed (km h^{-1})	% of total energy consumption 50 W pump	% of total energy consumption 100 W pump
10	2.7%	5.3%
20	1.3%	2.7%
30	0.9%	1.8%
40	0.7%	1.3%
50	0.5%	1.1%
60	0.4%	0.9%
70	0.4%	0.8%
80	0.3%	0.7%
90	0.3%	0.6%
100	0.3%	0.5%