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Research Paper

Thermal and electrical performance evaluations of series connected Li-ion batteries in a pack with liquid cooling

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HIGHLIGHTS

- Li-ion battery pack testing at 1C, 2C, 3C, 4C and drive cycle with liquid cooling.
- Three 20Ah $LiFePO_4$ cells connected in series tested with coolant at 10–40 °C.
- Battery pack temperature remains in required range (25–40 °C) with coolant at 30 °C.
- The maximum rise in battery pack temperature in only 1.1 °C with drive cycle.
- Energy efficiency and exergy destruction increase with rise in coolant temperature.

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ABSTRACT

Lithium-ion batteries are widely used in electric and hybrid electric vehicles due to their wide nominal range and high power densities. However, operating temperature, which has a pronounced effect on battery thermal performance and electrical performance, needs to be maintained within a specified range. In the present study, a Li-ion battery pack has been tested under constant current discharge rates (e.g. 1C, 2C, 3C, 4C) and for a real drive cycle with liquid cooling. The experiments are performed using cold plates at 10 °C, 20 °C, 30 °C, and 40 °C coolant temperatures to obtain thermal and electrical parameters. For this, three 20Ah $LiFePO_4$ prismatic cells are connected in series and a battery thermal management system is designed and developed for liquid cooling. To measure the temperature variation, 18 thermocouples are installed on the principal surface of all three cells: i.e., six on each cell. The results show that the battery pack temperature can be maintained within the required range at all four selected discharge rates with the coolant at 30 °C. The discharge capacity of the battery pack increases with increasing coolant temperature and is found to achieve a maximum of 19.11 Ah at a 1C discharge rate with the coolant at 40 °C.

1. Introduction

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) are cleaner and more energy efficient than conventional vehicles, but their performance depends strongly on battery pack performance [1]. The lithium-ion battery is currently the most advanced battery technology for EVs, HEVs, and Plug-In Hybrid Electric Vehicles (PHEVs) due to: 1) high specific energy and power densities [2]; 2) high nominal voltage and a low self-discharge rate [3]; and 3) long cycle-life and no memory effect [4]. However, the operating temperature has a great effect on discharging and charging performance parameters, such as power and energy capability, round trip efficiency, operation of the electrochemical system, life and life cycle cost [1]. A lower operating temperature (<20 °C) leads to a significant reduction in power capability and driving range, and even freezing phenomenon with electrolytes, while operating at high temperatures (>45 °C), results in battery degradation [5–7]. Further, the accumulation of heat in the battery pack, which is also known as thermal runaway, can lead to fire [8]. This is a serious issue regarding the safety and life of the battery. The low temperature, especially during winter, may also affect the performance of the EV batteries in various ways, such as difficulty in charging, short driving range [9].

Usually, a battery thermal management system (BTMS) is required to maintain the temperature of the battery pack in the

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Nomenclature

C_p	specific heat at constant pressure, J kg^{-1} K^{-1}
ex	specific exergy, J kg^{-1}
$\dot{Ex}$	exergy rate, W
G	Gibbs free energy, J mol^{-1}
h	specific enthalpy, J kg^{-1}
I	current, A
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
n	number of electrons per mole
$\dot{Q}$	heat transfer rate, W
s	specific entropy, J kg^{-1} K^{-1}
S	entropy, J K^{-1}
t	time, s
T	temperature, K
V	cell potential, V

Greek letters

η	energy efficiency, %

Subscripts

0	ambient
batt	battery
cool	coolant
D	destruction
e	exit
ele	electrical
exp	experimental
gen	generation
i	inlet
k	any number
theo	theoretical

Acronyms

BMS	Battery Management System
BTMS	Battery Thermal Management System
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
HTF	Heat Transfer Fluid
HWFET	Highway Fuel Economy Test
LFP	Lithium Iron Phosphate
NI	National Instrument
PHEV	Plug-in Hybrid Electric Vehicle
UDDS	Urban Dynamometer Driving Schedule

required range. Each battery works well within a specific temperature range. For example, Li-ion batteries perform best at a temperature between 25 °C and 40 °C [1,10], where they have a good balance between performance and life. Traditionally, an active or a passive thermal management system is used in EVs and HEVs, where an active BTMS uses air or liquid as the heat transfer fluid (HTF). Studies show that passive air systems are not capable of managing battery temperature within the required range at a high discharge rate [11,12]. Liquid cooling, which is more compelling because of its higher specific heat content contrasted with air cooling, occupies less volume, yet brings more complexities and a higher cost and weight [13].

Various active and passive BTMSs have been studied by researchers [14–16], where air and various liquids are used as HTF. Keller and Whitehead [17] studied the effect of battery operation in extreme temperature conditions without a BTMS and with an air or liquid BTMS. It was found that the vehicle driving range is lower in the absence of a BTMS, as heat spreads across the battery pack due to high ambient temperatures. This can lead to premature cell failure and seasonal driving variability. The study also identified that the mileage of the vehicle can be increased up to 20% by using a BTMS. Furthermore, the temperature distribution can be reduced to 2.3 °C and 4.0 °C compared to 11.6 °C for a non-managed pack, by circulating air and liquid, respectively. Kuper et al. [18] examined the different active cooling systems using air, water and a refrigerant, and also studied heat generation in batteries. They formulated the increase in battery temperature over time, based on internal heating and cooling rates. The study shows that the maximum and minimum cell temperatures should be maintained within a 3–5 K range to prevent 25% acceleration of the ageing kinetics and up to 50% variance in power capability. In an another study, Lu et al. [19] have investigated the use of forced air for thermal management of densely packed EV battery. Numerical analysis of 252 cylindrical Li-ion cells arranged in 6 rows is performed using Ansys FLUENT. The result shows that the maximum temperature of the battery decreases gradually with an increase in cooling channel size. However, continuous increase in cooling channel size is not an effective method to decrease the maximum temperature of the battery.

Some studies show that liquid metal can also be used as an HTF [20]. Yang et al. [21] have investigated the use of liquid metal for thermal management of Li-ion batteries in place of water. The result shows a less pump power consumption, a lower and more uniform module temperature with the use of liquid metal compared to water. However, heavy weight, relatively high cost, and incompatibility with cooling jacket material (aluminium) are the major drawbacks of using liquid metal for thermal management of Li-ion batteries.

A well-designed BTMS is required in order to remove generated heat and to maintain the required temperature of the battery pack. Existing EVs/HEVs, such as the Chevrolet Volt and Tesla Model S, use an active liquid cooling system for the battery [22]. In the case of BMW i3, no liquid coolant is used between the cells, as the bottom of the battery case is cooled by the refrigerant. The Chevy Volt HEV has a T-shaped battery pack that contains 288 prismatic cells. The Chevy Volt TMS has a number of heat sources and cooling loops which work independently of each other [23]. A premixed solution of Dexcool coolant and deionized water is used as the HTF. Cold plates are used between the cells to circulate the HTF (coolant) and to absorb heat from the cells [24]. A comparison of air, liquid and refrigerant cooling of the battery pack under different operating conditions shows that active liquid circulation is most effective to maintain uniform battery temperature and reducing entropy generation rate [25]. The application of battery heating system during low temperature is also studied by the various researcher [9,26]. However, the scope of the present study limited to liquid cooling.

Although liquid cooling systems have been extensively studied, there is a lack of knowledge regarding at what particular coolant temperature the battery temperature can be managed within the required limit (25–40 °C) at various discharge rates. There is also a lack of experimental data in the literature related to the thermal and electrical performance of a Li-ion battery pack at high discharge rates for different coolant temperatures. The main objective of this paper is to find the coolant temperature at which the battery temperature can be managed within the required range at low as well as high discharge rates. Therefore, an experimental setup is developed using cold plates and three