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Coupled electrochemical thermal modelling of a novel Li-ion battery pack thermal management system

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HIGHLIGHTS

- Three-dimensional electrochemical thermal model of Li-ion battery pack using computational fluid dynamics (CFD).
- Novel pack design for compact liquid cooling based thermal management system.
- Simple temperature estimation algorithm for the cells in the pack using the results from the model.
- Sensitivity of the thermal performance to contact resistance has been investigated.

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ABSTRACT

Thermal management system is of critical importance for a Li-ion battery pack, as high performance and long battery pack life can be simultaneously achieved when operated within a narrow range of temperature around the room temperature. An efficient thermal management system is required to keep the battery temperature in this range, despite widely varying operating conditions. A novel liquid coolant based thermal management system, for 18,650 battery pack has been introduced herein. This system is designed to be compact and economical without compromising safety. A coupled three-dimensional (3D) electrochemical thermal model is constructed for the proposed Li-ion battery pack. The model is used to evaluate the effects of different operating conditions like coolant flow-rate and discharge current on the pack temperature. Contact resistance is found to have the strongest impact on the thermal performance of the pack. From the numerical solution, a simple and novel temperature correlation of predicting the temperatures of all the individual cells given the temperature measurement of one cell is devised and validated with experimental results. Such coefficients have great potential of reducing the sensor requirement and complexity in a large Li-ion battery pack, typical of an electric vehicle.

1. Introduction

Li-ion batteries exhibit low performance at low temperatures [1] and low life expectancy at high temperatures [2–4]. Optimal operating temperature for a Li-ion battery is close to human comfort temperature [5]. It has been reported that temperature variation in a single cell can have significant effect on the pack performance [6]. Considering the wide operating temperature range of an electric vehicle and high cost of lithium-ion battery, it is extremely important to design an efficient thermal management system (TMS) that can keep the Li-ion battery pack temperature within the prescribed limits. Besides, protection from and avoidance of thermal runaway condition is another important function of the thermal management system [7]. Optimum thermal management is required for high performance, long life and safe operation by avoiding low and high temperatures and thermal runaway respectively [7].

Although air cooling is one of the simplest cooling system, low heat capacity and low thermal conductivity of air are the main drawbacks of such a system. As the thermal conductivity of air is low, the rate of heat transfer from battery to air is also low. Similarly, as the heat capacity of air is low, it can only carry away a small amount of heat from the battery pack. Therefore, for effective air cooling, high flow volume and high mixing rate are required to mitigate low heat capacity and thermal conductivity respectively.

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Nomenclature

A	fitting coefficients for NCA OCP
a	volumetric area ($m^2\ m^{-3}$)
B	fitting coefficients for NCA entropy generation
C	specific heat/heat capacity ($J\ kg^{-1}\ K^{-1}$), thermal coefficient
c	concentration of Li ($mol\ m^{-3}$)
D	diffusivity ($m^2\ s^{-1}$)
E	potential (V)
F	faraday constant (96,485 Q mol^{-1})
$f_{\pm}$	mean molar salt activity coefficient
i	current density ($A\ m^{-2}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
P	pressure (Pa)
R	radius (m)
R_g	universal gas constant (8.3145 $J\ mol^{-1}\ K^{-1}$)
r	radial coordinate (m)
Q	heat source ($W\ m^{-3}$)
T	temperature (K)
t	time (s)
t_+^0	transference number of the electrolyte
$\vec{u}$	flow velocity vector ($m\ s^{-1}$)
V	cell voltage (V)
x	through plane coordinate (m)
y	cathode state of charge

Greek letters

α	transfer coefficient
ε	porosity
κ	ionic conductivity ($S\ m^{-1}$)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
σ	electronic conductivity ($S\ m^{-1}$)
ϕ	potential (V)

Subscripts

a	anode
c	cathode
e	electrolyte phase
eq	equilibrium
exp	experimental
i	particle interface/surface
irr	irreversible
mod	model
n	intercalation
p	constant pressure, particle
rev	reversible
s	solid (electrode) phase
tot	total
ohm	ohmic heat generation
0	initial condition, exchange

Superscripts

eff	effective
max	maximum
ref	reference

In a constrained space like a passenger vehicle, available volume may be limited and high mixing rate which requires a highly turbulent flow, can be a source of noise. Compared to air cooling liquid cooling is compact and efficient. However, liquid cooling has to be leak proof and common coolants like Dexcool, may contribute to a safety hazard. Nevertheless, leading hybrid and electric vehicles used liquid cooling [8–10]. Lately advanced cooling methods such as use of phase change materials (PCM) has been applied for Li-ion battery thermal management [11]. There have been efforts to improve the electronic and thermal conductivity of the electrodes to reduce heat generation through optimizing particle size, adding conductive binder, blending etc. [12–18]. Addition of graphene, in the hydrocarbon based PCM, is found to increase the thermal conductivity by orders of magnitude while retaining the latent heat based heat storage capacity [17,18]. Despite such progress in material properties, the presence of an active and external thermal management system is inevitable in almost all large format Li-ion battery packs used in electric or hybrid-electric vehicles.

In electronic cooling – generally air cooling is preferred as it is a bad conductor of electricity. As a result, it offers a strong resistance to any possible short circuit. Since the heat capacity of air is low, design of flow path is critical to achieve optimal cooling. Air temperature at all the cells have to be low enough for effective heat transfer from cell to air. Considering the three-dimensional nature of the flow around the cells in a battery pack and spatial variance in heat generation, computational fluid dynamics simulation of the battery pack has evolved as an effective design and optimization tool to address thermal management problems [19–24]. It has been found through CFD simulation of forced air cooling of battery pack, that no single arrangement could offer the best performance in all aspects [19,20]. A three dimensional CFD solution that includes electrochemical model of the full battery pack can be computationally expensive. Therefore, partial models have been introduced for design after extensive validation with experiment [21]. Accurate CFD simulation of air cooling have been used as the basis of reduced order model [22] and introducing novel concepts like alternating flow path [23] or bi-directional flow method [24] have effectively maintained temperature uniformity for a given pack geometry at the cost of extra volume. It is clear from these investigations that air cooling could be adequate for small and medium size battery packs.

For larger battery packs operating at high discharge rates (typical of EVs and HEVs) liquid cooling is found to be more effective [25]. Since direct convection cooling through liquid coolant is not possible it is generally done by passing through a “cold plate”. A “cold plate” refers to a metal plate (high thermal conductivity) with built-in mini-channels for coolant flow [26]. The Li-ion batteries are kept in close contact with the plate. Controlling the coolant flow rate, the battery temperature can thus be controlled [26]. CFD simulation based “cold plate” optimization has been reported [27–29]. However, in these investigations the electrochemistry of battery is not considered. The battery heat generation is included as a uniform input (source or flux) to the model. The flat shape of the “cold plate” makes it easy to transfer heat from pouch cells. However, for a pack made of cylindrical cells the applicability of “cold plate” is low.

To avoid the potential problems of liquid cooling, heat pipes have been employed to transfer heat from battery and transport to an appropriate heat sink [30–32]. Heat pipe is popular in the electronic cooling industry due to its compactness and high effective conductivity. Similarly, phase change material (PCM) has also emerged as a potential alternative for battery TMS [33–35]. The greatest advantage of PCM is that it can keep the cells within a narrow band of temperature around its melting point temperature. On the other hand, low thermal conductivity of PCM makes it difficult to remove the accumulated heat from the PCM system. As mentioned earlier, graphene augmented PCM might be able to mitigate this problem [17,18].