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Electrochemical-thermal Modeling to Evaluate Active Thermal Management of a Lithium-ion Battery Module

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ABSTRACT

Lithium-ion batteries are commonly used in hybrid electric and full electric vehicles (HEV and EV). In HEV, thermal management is a strict requirement to control the batteries temperature within an optimal range in order to enhance performance, safety, reduce cost, and prolong the batteries lifetime. The optimum design of a thermal management system depends on the thermo-electrochemical behavior of the batteries, operating conditions, and weight and volume constraints. The aim of this study is to investigate the effects of various operating and design parameters on the thermal performance of a battery module consisted of six building block cells. An electrochemical-thermal model coupled to conjugate heat transfer and fluid dynamics simulations is used to assess the effectiveness of two indirect liquid thermal management approaches under the FUDC driving cycle. In this study, a novel pseudo 3D electrochemical-thermal model of the battery is used. It is found that the cooling plate thickness has a significant effect on the maximum and gradient of temperature in the module. Increasing the Reynolds number decreases the average temperature but at the expense of temperature uniformity. The results show that double channel cooling system has a lower maximum temperature and more uniform temperature distribution compared to a single channel cooling system.

1. Introduction

Lithium-ion (Li-ion) batteries are considered as suitable energy storage devices for the electric vehicles (HEV-EV) due to their high specific energy and power densities [1,2] and low self-discharge rate [3]. The main challenges to the wide employment of Li-ion batteries in EV and HEV are safety and cost related to the battery lifespan [4]. These challenges are strongly coupled to the thermal behavior of batteries. One of the most catastrophic safety issues of a lithium-ion battery is cascading thermal runaway, where multiple cells in a battery fail due to an individual cell failure. The conductivity of the electrolyte increases with temperature, causing more current to be directed to hotter sections of a battery. This generates more heat in hotter region, raising the temperature and allowing even more current to pass through it. This positive feedback has the potential to lead to the battery thermal runaway [5]. Another concern is temperature non-uniformity in the battery module and pack. The temperature difference in a module causes electrical imbalance over time which leads to the state of charge (SOC) mismatch between the cells. Hence, it is critical to retain the li-ion batteries maximum temperature within the safe limits and reduce the temperature non-uniformity of the battery and the module.

There are two major strategies for thermal management in electric vehicles. An active method by using air or a liquid as coolant [6,7] or a passive approach by employing phase change materials (PCM) [8,9]. Air cooling can moderate the batteries temperature rise, but in aggressive driving cycles and/or at high operating temperatures it will result in a large non-uniform temperature distribution in the battery module [10]. Liquid cooling with water, oil or refrigerants as the heat transfer medium shows higher thermal efficiency due to the higher heat capacity of liquids compared to air [11,12].

A number of numerical investigations have been performed on the liquid cooling of Li-ion batteries. Karimi and Li [6] simulated the effects of various cooling scenarios on the temperature and voltage distribution using an empirical lumped battery thermal model. They showed that a cooling strategy based on distributed air or liquid convection can be an efficient and cost-effective method. Yeow et al. [13,14] utilized uniform thermophysical properties and equivalent circuit heat generation model to compare single and dual cold plate cooling systems. Their studies

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Nomenclature

c_s	concentration of lithium in the active material particles ($mol\,m^{-3}$)
c_l	electrolyte concentration ($mol\,m^{-3}$)
C_p	Specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D_s	diffusion coefficient of lithium in the active material ($m2\,s^{-1}$)
D_l	diffusion coefficient of electrolyte ($m2\,s^{-1}$)
E_{aD}	diffusion activation energy ($kJ\,mol^{-1}$)
E_{aR}	reaction activation energy ($kJ\,mol^{-1}$)
$f_{\pm}$	average molar activity coefficient
F	Faraday's constant ($C\,mol^{-1}$)
j_0	exchange current density ($A\,m^{-2}$)
j_n	local charge transfer current density ($A\,m^{-2}$)
k_0	reaction rate constant ($m^{2.5}\,mol^{-0.5}\,s^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	thickness of each battery component (m)
P	coolant pressure (Pa)
$\dot{Q}$	coolant volume flow rate ($m^3\,s^{-1}$)
R	gas constant, 8.314 ($J\,mol^{-2}\,K^{-1}$)
r	radius distance variable of electrode particles (m)
r_0	radius of electrode particles (m)
S_a	specific surface area (m^{-1})
t	time (s)
t_+	transferring number of Li^+
T	temperature (K)
T_a	ambient temperature (K)
U_{eq}	open circuit potential of the electrode (V)
$U_{eq,ref}$	open circuit potential under the reference temperature (V)
V	coolant velocity ($m\,s^{-1}$)

Greek letters

α_a	anode transfer coefficient
α_c	cathode transfer coefficient
γ	Bruggeman tortuosity exponent
ε_s	active material volume fraction
ε_l	electrolyte volume fraction
δ	active material thickness (m)
η	local surface overpotential (V)
θ	dimensionless battery volume
ρ	density ($kg\,m^{-3}$)
σ_s	electronic conductivity in solid phase material ($S\,m^{-1}$)
σ_l	ionic conductivity of electrolyte ($S\,m^{-1}$)
Φ_s	solid phase potential (V)
Φ_l	electrolyte phase potential (V)
ψ	dimensionless module volume

Subscripts and superscripts

0	initial or equilibrated value average
eff	effective value
max	maximum
l	electrolyte phase
s	solid phase
w	water

showed that the dual cold plate design presents considerably higher cooling capacity than single cold plate design. Xun et al. [15] developed numerical and analytical models based on an empirical lumped battery thermal model to study the effects of cooling channel and battery stack geometries on the battery thermal management system (BTMS). They suggested that a counter-flow arrangement of the cooling channels or periodic changing of the coolant flow direction may improve the BTMS performance. Liu et al. [16] compared the temperature distribution in a Li-ion battery stack with liquid and PCM thermal management. Simulations were performed on a 20 Ah flat battery stack utilizing a lumped thermal model. The results indicated that the liquid cooling is generally more efficient than the PCM method, although PCM caused more uniform temperature distribution. Tong et al. [7] numerically studied the effects of operating and design parameters of a liquid cooling system on the performance of a battery pack. They calculated the battery heat generation through a 2-dimensional coupled thermal-electrochemical model. The results indicated that the rise in the average temperature and the temperature distribution non-uniformity were intensified as the number of batteries in the pack increased. Furthermore, it has been shown that increasing the coolant velocity or the cooling plate thickness can reduce the battery pack average temperature and decrease the non-uniformity of local temperature distribution. Chen et al. [17] compared four air and liquid cooling systems with different designs. They used a 1RC equivalent circuit model with lumped thermal properties to estimate battery thermal behavior under constant current discharge. The results showed that an indirect cooling system was more practical than direct approach large-format Li-ion battery cooling.

Thermal management investigations in the module and pack levels are mainly conducted either by lumped thermal models with heat generation data obtained from experiments and equivalent circuit models or by 2D electrochemical-thermal models. This is due to the significant computational cost required for 3D coupled electrochemical-thermal models. However, accurate assessment of battery electrical and thermal responses to different cooling scenarios needs 3D coupled electrochemical-thermal models. The numerical studies on the liquid BTMS are commonly performed during constant current discharge cycles. Nevertheless, electric and hybrid electric vehicles driving cycles, and consequently batteries charge/discharge cycles, show complex patterns that cannot be precisely modeled with constant current discharge rates.

In this study, a three dimensional coupled electrochemical-thermal model for an NCA Li-ion battery as well as experimental validation of the electrical and thermal results are presented. The effects of cooling system design parameters and coolant inlet velocity on the electrical and thermal behavior of a lithium ion battery module during a standard hybrid electric vehicle driving cycle are investigated comprehensively.

2. Numerical Model

2.1. Battery Modeling

In the current work, a fast simulation pseudo three dimensional electrochemical-thermal model is used. The numerical results are compared with a commercial 4 Ah Li-ion battery with graphite anode coated on a copper foil (as the negative current collector) and NCA cathode material coated on an aluminum foil. The battery consists of 20 parallel connected cells with double-side coated current collectors, and a highly porous polymeric separator. The cell dimensions are about $8 \times 46 \times 138$ mm. The model is based on the coupling of mass, charge, and energy conservations, as well as electrochemical kinetics. Fig. 1 represents the 1D and 3D computational domains and how they are coupled to form the pseudo 3D model. The current model uses a 1D local electrochemical cell unit to find the reaction and polarization heat generations as well as the electrolyte concentration distribution in the active battery material. The values of concentration are inserted in a 3D electric current conservation solver to calculate the distributed Ohmic heat generation. Finally, the 3D energy conservation