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Research Paper

Electrochemical thermal modeling and experimental measurements of 18650 cylindrical lithium-ion battery during discharge cycle for an EV

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HIGHLIGHTS

- Designed and developed the battery thermal testing system.
- Developed ECT model using ANSYS Fluent.
- Studied the temperature and voltage profile at different discharge rates.
- Validated the model with the experimental data.

ARTICLE INFO

Keywords:
Lithium-ion battery
Electrochemical thermal model
Thermal analysis
ANSYS

ABSTRACT

Study of thermal performance in lithium-ion battery cell is crucial which directly affects the safety. Even though the operation of a lithium-ion battery cell is transient phenomena in most cases, most available thermal models for lithium-ion battery cell predicts only steady-state temperature fields. This paper presents a mathematical model to predict the transient temperature and voltage distributions of 18650 cylindrical lithium-ion battery at different discharge rates. For this, the 18650 cylindrical lithium-ion battery cell is tested inside the lab with an air-cooling method by four thermocouples mounted on the battery surface under four constant current discharge rates of 1 C, 2 C, 3 C, and 4 C in order to provide quantitative data regarding thermal behavior of lithium-ion batteries. Later, the numerical model is developed using ANSYS CFD software and it is found that the model predictions are in good agreement with experimental data for temperature and voltage profiles. The highest temperature is 46.86 °C at 4 C discharge rate as obtained from simulation. The results also show that the increased C-rates results in increased temperature on the principle surface of the battery.

1. Introduction

Increasing environmental awareness and depleting fuels sources are the main issues in the automotive industry and therefore, electric vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs) are projected as one of the most sustainable solutions for future transport. These days, lithium-ion batteries are gaining widespread acceptance in the development of EVs, HEVs, and PHEVs due to: (1) high specific energy and power densities [1]; (2) high nominal voltage and low self-discharge rate [2]; and (3) long cycle-life and no memory effect [3]. To extend the life of battery, precautions must be taken during discharging and charging since, for example exceeding voltage, current or power limits may result in battery cell damage. The possibility of thermal runaways also occurs if care is not properly taken [4]. Moreover, lithium-ion polymer batteries must be carefully monitored and managed (electrically and thermally) to avoid safety (inflammability) and performance related issues [5–8].

There are various papers in the open literature available for battery thermal modeling, using different approaches such as artificial neural network [9–11], finite element model (FEM) [12] or lumped parameter model (LPM) [13], linear parameter varying (LPV) model [14], or partial differential equation (PDE) model [15], CFD models [16–18]. Battery modeling based on electrochemical equations provides a deep understanding of the physical and chemical process inside the battery which makes it useful when designing a cell, but high computational time makes these models improper for applications with high dynamics. The first electrochemical modeling approach to porous electrodes with battery applications was presented by Newman and Tiedemann in 1975 [19]. In the porous electrode theory, the electrode is treated as a

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Nomenclature

a_s	solid/electrolyte interfacial area per unit volume or active surface area per electrode unit volume for electron transfer reactions [1/cm]
A	area [m^2]
c_p	specific heat capacity [J/kg °C]
$C_{p,p}$	specific heat for positive tab [J/kg-K]
$C_{p,n}$	specific heat for negative tab [J/kg-K]
$C_{p,a}$	specific heat for active zone [J/kg-K]
C_e	concentration of lithium in electrolyte phase [mol/m^3]
C_s	concentration of lithium in solid phase [mol/m^3]
$C_{s,p,\max}$	maximum solid Li^+ Concentration for positive electrode [mol/m^3]
$C_{s,n,\max}$	maximum solid Li^+ Concentration for negative electrode [mol/m^3]
D_s	mass diffusion coefficient of lithium-ion in electrolyte
$D_{s,p}$	reference diffusivity for positive electrode [m^2/s]
$D_{s,n}$	reference diffusivity for negative electrode [m^2/s]
$D_{s,ref}$	reference solid diffusion coefficient
D_e^{eff}	effective diffusion coefficient
E_d	activation energy that controls temperature sensitivity of D_s [kJ/mol]
E_r	activation energy that controls temperature sensitivity of k_m [kJ/mol]
$f_\pm$	molecular activity coefficient of the electrolyte also called electrolyte activity coefficient
F	Faraday's constant [96485 Columb/mol]
i_0	exchange current density [A/m^2]
I	current [A]
j^{Li}	transfer current resulting from lithium insertion/de-insertion at the electrode/electrolyte interface [A/m^2]
k	ionic conductivity of electrolyte [S/m]
k_p	reference rate constant for positive electrode [$mol/m^2\,s/(mol/m^3)^{1.5}$]
k_n	reference rate constant for negative electrode [$mol/m^2\,s/(mol/m^3)^{1.5}$]
$k_{m,ref}$	reference reaction rate coefficient
k^{eff}	effective diffusional conductivity [S/m]
k_D^{eff}	effective ionic conductivity [S/m]
l_n	length of negative electrode [μm]
l_s	length of separator [μm]
l_p	length of the positive electrode [μm]
L	overall length ($L = l_n + l_s + l_p$) in [μm]
n	number of electrons
$\dot{q}$	heat generation rate [W]
r	radial coordinate along active material particle
R	resistance [Ω]
R	universal gas constant [8.3143 kJ/kg mole. K]
R_s	radius of solid active material particle [μm]
$R_{s,p}$	particle radius for positive electrode [μm]
$R_{s,n}$	particle radius for negative electrode [μm]
T	temperature [°C or K]
t_+^0	transfer number of lithium-ion
t	time [s]
U	electrode potential of the reaction or thermodynamic open circuit potential [V]
V	cell voltage or cell potential [V]

Greek symbols

α	thermal diffusivity [m^2/s]
φ	energy dissipation rate
β	Burggeman porosity exponent
ρ	density [kg/m^3]
∇	gradient operator
$\varnothing_s$	solid phase potential [V]
$\varnothing_e$	electrolyte phase potential [V]
σ^{eff}	effective conductivity [S/m]
σ_+	effective electrical conductivity for positive electrode [S/m]
σ_-	effective electrical conductivity for negative electrode [S/m]
ϵ_e	volume fraction of electrolyte phase in electrode
ϵ_s	volume fraction of solid particle (active material) in electrode
ϵ_f	volume fraction of filler material in electrode
$\propto_a$	transfer coefficient of anode
$\propto_c$	transfer coefficient of the cathode

Subscripts

∞	ambient
o	initial
a	anode
c	cathode
e	electrolyte
f	filler
exp	experimental
n	negative electrode
oc	open circuit
p	positive electrode
ref	reference
s	separator
sim	simulated
tot	total
x,y,z	Cartesian coordinate directions

Superscripts

°	degree
Li	lithium
eff	effective
ECH	electrochemical heat

Acronyms

ANSYS Inc.	American Computer-aided engineering software developer
C	capacity
CC	constant-current
CFD	computational fluid dynamics
ECT	electrochemical thermal
ECM	equivalent circuit-based modeling
EV	electric vehicle
FCV	fuel cell vehicle
FEA	finite element analysis
FEM	finite element method
HEV	hybrid electric vehicle
GAIA	green and intelligent automotive
Li-ion	lithium ion
$LiFePO_4$	lithium iron phosphate
LCM	lumped capacitance model
LFP	lithium phosphate
LPM	lumped parameter model
LPV	linear parameter varying
LabVIEW	laboratory virtual instrument engineering workbench
MSMD	multi scale multi domain
NiMH	nickel metal hydride
OCV/OCP	open circuit voltage/open circuit potential