Review

Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review

Huaqiang Liu[a], Zhongbao Wei[b], Weidong He[c], Jiyun Zhao[a],[*]

[a] Department of Mechanical and Biomedical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong Special Administrative Region
[b] Energy Research Institute, Nanyang Technological University, Singapore 637459, Singapore
[c] School of Energy Science and Engineering, University of Electronic Science and Technology, Chengdu, Sichuan 611731, PR China

ABSTRACT

Electrical vehicles have the capability to lessen the severe threats of energy crisis and environment pollution. The Lithium ion battery as a promising solution for the energy storage in vehicular applications is briefly introduced in this paper. The adverse effects of improper temperature, including performance degradation, potential thermal runaway, temperature non-uniformity and low temperature performance are described afterwards. The thermal model, electrochemical model, equivalent circuit model and electrochemical/electrical-thermal coupling methods are also elaborated for the accurate battery modeling. More importantly, this review detailedly summarizes the progress on battery thermal management systems (BTMSs) including the air, liquid, boiling, heat pipe and solid-liquid phase change based strategies during recent years. Influence factors and development focus of different BTMSs are stated elaborately. Passive cooling systems utilizing the latent heat during the phase change process are more attractive options compared to the conventional single phase forced air and liquid cooling methods. However, there still exist some challenges to be addressed before commercializing. In addition, different methods could be combined to meet the requirements of various applications. The improvement of these existing BTMSs is supposed to be paid more attention to enhance Li-the performance and safety of Li-ion batteries.

1. Introduction

Nowadays, people all over the world are being posed to the threat of energy crisis and severe environment pollution. However, driven by the growing improvements in economic levels, the global demands for energy resources, especially for the fossil fuels (e.g. oil), are still rising rapidly. According to the statistics from BP Statistical Review of World Energy 2016 [1] and BP Energy Outlook 2016 [2], the global oil consumption grew by 1.9 million barrels per day, nearly two-thirds of which was attributed to the transportation sector. To reduce the emissions of pollutants and greenhouse gases, increasing attentions have been paid to the development of clean energy vehicles, including pure electric vehicles (EV), hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV), which are more energy-efficient and environment friendly than the traditional internal combustion engine systems [3]. Anderson et al. [4] indicated that the employment of EVs could bring about a remarkable reduction of greenhouse gas emissions by almost 40% if the electric power resources are renewable (e.g. solar, wind, etc.).

The key task of developing clean energy vehicles is to find a suitable

energy storage system which can support high driving mileage and fast acceleration. Various power batteries have been proposed, such as lead-acid (Pb-acid), nickel based, sodium based and lithium-ion (Li-ion) batteries [9]. Some key indicators for evaluating these battery systems are listed in Table 1. Among all these electrochemical systems, Li-ion batteries are the most promising choices for EVs and HEVs due to their superior characteristics of high specific energy and power, long cycling life, and low self-discharge rates, as indicated in Table 1. Therefore, Li-ion batteries have been widely employed in our daily lives, including wrist watches, smart phones, laptops and many other portable electronics [10].

However, in spite of its attractive prospect, Li-ion battery based EVs have not been widely adopted by consumers. The major hindrances in regard with the battery system include the high cost, limited calendar life, safety concerns, and the temperature-caused degradation [11]. Currently, extensive efforts have been made to find better electrode materials to enhance the specific energy, specific power and lifetime. However, the research in the thermal issues of Li-ion batteries under various conditions and the development of battery thermal management systems (BTMSs) have not been adequately addressed although

Nomenclature

a_s	specific interfacial area of solid phase, $\mathrm{m^2\,m^{-3}}$
A	surface area of active material, $\mathrm{m^2}$
A_s	cell surface area exposed to the convection coolant, $\mathrm{m^2}$
B_i	Biot number
c_e	concentration of lithium ions in electrolyte phase, $\mathrm{mol\,m^{-3}}$
c_s	concentration of lithium ions in solid phase, $\mathrm{mol\,m^{-3}}$
C_0	battery capacity, A h
C_p	battery specific heat capacity, $\mathrm{J\,kg^{-1}\,K^{-1}}$
D_s	mass diffusion coefficient of lithium in solid phase, $\mathrm{m^2\,s^{-1}}$
E_a	activation energy, J
$f_\pm$	molecular salt activity coefficient
F	faraday constant, $96{,}485\ \mathrm{C\,mol^{-1}}$
h	heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
h_s	cell heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
i	current per unit volume $\mathrm{A\,m^{-3}}$
i_e	current density in electrolyte phase, $\mathrm{A\,m^{-2}}$
i_n	transfer current density, $\mathrm{A\,m^{-2}}$
i_o	exchange current density, $\mathrm{A\,m^{-2}}$
i_s	current density in solid phase, $\mathrm{A\,m^{-2}}$
I	applied current density, A
I_L	current in the load circuit, A
j_n	pore-wall flux across interface, $\mathrm{mol\,m^{-2}\,s^{-1}}$
k_a	anodic reaction rate constant, $\mathrm{m^3\,s^{-1}}$
k_c	cathodic reaction rate constant, $\mathrm{m^3\,s^{-1}}$
k^{eff}	effective ionic conductivity, $\mathrm{S\,m^{-1}}$
L	total thickness of the cell, m
L_n	thickness of negative electrode, m
L_{sep}	thickness of separator, m
n	number of electrons participating in the reaction
P_{fluid}	fluid pressure drop, Pa
$\dot{q}$	rate of internal heat generation per unit volume $\mathrm{W\,m^{-3}}$
$\dot{Q}$	heat generation rate of the battery, W
r	distance in radial direction, m
R_1	equivalent resistance in the load circuit, Ω
R_g	universal gas constant, $8.3145\ \mathrm{J\,mol^{-1}\,K^{-1}}$
R_i	internal equivalent resistance of unit volume, $\Omega\,\mathrm{m^{-2}}$
R_s	radius of solid active material particle, m
ΔS	entropy change, $\mathrm{J\,mol^{-1}\,K^{-1}}$
t	time, s
t_+^0	transference number of the lithium ions with respect to the

	velocity of solvent
T	temperature, K
U_L	load voltage, V
U_{OC}	open-circuit potential, V
U_{RC}	voltage across the RC network, V
V	cell operating voltage, V

Greek symbols

α_a	transfer coefficient of anode
α_c	transfer coefficient of cathode
σ	Stefan-Boltzmann constant, $5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$
σ^{eff}	effective electronic conductivity of the solid phase, $\mathrm{S\,m^{-1}}$
ρ	battery density, $\mathrm{kg\,m^{-3}}$
λ	thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
ε	emissivity of the cell surface
ε_e	volume fraction/porosity of electrolyte
φ	angle in cylindrical-coordinate system, rad
$\varnothing_s$	potential in the solid phase, V
$\varnothing_e$	potential in the electrolyte phase, V
η_s	surface overpotential, V
Ψ	transport and kinetic parameters

Subscripts

ref	with respect to a reference state
amb	ambient environment or coolant
avg	with respect to average temperature
rad	equivalent radiative coefficient
t	equivalent coefficient which consists of the convection and radiation
σ	with respect to temperature difference
x	x coordinate
y	y coordinate
z	z coordinate
r	radial coordinate

Superscripts

max	the maximum value in the particle of electrode
$surf$	the value on the surface of the particle of electrode
avg	the average value in the particle of electrode

they have a large impact on the performance, lifespan and security of battery. The acceptable operating temperature range for Li-ion batteries is -20 to $60\,^\circ\mathrm{C}$ [12] and to maintain its optimal performance, a narrow temperature range between $15\,^\circ\mathrm{C}$ and $35\,^\circ\mathrm{C}$ is recommended by Pesaran et al. [13]. Temperatures outside the desired range will result in significant capacity loss. Motloch et al. indicated that every degree's

Table 1
Some properties of different electric vehicle batteries.
adapted from [5–8]

Type	Specific energy (W h kg^{-1})	Specific power (kW kg^{-1})	Nominal cell voltage (V)	Life cycles[1]	Charge time (h)	Self-discharge rate[2] (%)
Lead-acid	25–40	150–250	2	200–700	8	5
Nickel-cadmium	45–80	200	1.2	500–2000	1	20
Nickel-metal hydride	60–120	200	1.2	500–1000	1	30
Nickel-iron	50	100	1.2	2000	/	20–40
Nickel-zinc	70	150	1.7	300	/	20
Sodium-sulphur	100	150–200	2	~1000[3]	8	Quite low
Sodium metal chloride	100	150	2	> 1000[4]	8	/
Li-ion	110–180	300	3.6	> 1000	2–3	10
Li-polymer	100–130	300	3.6	300–500	2–4	10

[1] Up to 80% capacity.
[2] Loss per month.
[3] ~1000 means no more than 1000.
[4] > 1000 means no less than 1000.