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Research Paper

Thermal design and simulation of mini-channel cold plate for water cooled large sized prismatic lithium-ion battery

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HIGHLIGHTS

- Design of battery thermal management system with water cooling for LFP battery.
- Design of mini-channel cold plates in NX and meshing in ICEM-CFD.
- ANSYS CFD modeling of mini channel cold plates.
- Temperature and velocity contours are obtained at different discharge rates and boundary conditions.
- Results may contribute towards thermal safety of Lithium-ion batteries.

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ABSTRACT

This paper has presented a comparative study of the temperature and velocity distributions within the mini-channel cold plates placed on a prismatic lithium-ion battery cell using experimental and numerical techniques. The study was conducted for water cooling methods at 1C and 2C discharge rates and different operating temperatures of 5 °C, 15 °C, and 25 °C. A total of nineteen thermocouples were used for this experimental work, and were purposefully placed at different locations. Out of nineteen, ten T-type thermocouples were placed on the principal surface of the battery, and four K-type thermocouples were used to measure water inlet and outlet temperature. Computationally, the k-ε model in ANSYS Fluent was used to simulate the flow in a mini-channel cold plate, and the data was validated with the experimental data for temperature profiles. The present results show that increased discharge rates and increased operating temperature results in increased temperature of the cold plates. Furthermore, the thermocouple sensors nearest the electrodes (anode and cathode) measured the higher temperatures than the sensors located at the center of the battery surface.

1. Introduction

To alleviate the environment issues, the automotive industry has been forced to move towards sustainable vehicles such as electric vehicles (EVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell vehicles (FCVs). In present days, lithium-ion batteries are the most cutting-edge battery technology used in the production of EVs, HEVs, and PHEVs [1]. Their broad usage is due to: (1) high specific energy and power densities [2,3]; (2) high nominal voltage and low self-discharge rate [4]; and (3) long cycle-life and no memory effect [5]. To prolong the life of batteries, precautions must be taken during discharging and charging since, exceeding the voltage, current or power limits may result in battery cell damage. The possibility of thermal runaways also occurs if care is not properly taken [6,7]. Moreover, lithium-ion polymer batteries must be carefully monitored and managed (electrically and thermally) to avoid safety and performance related issues [8–11].

The optimal operation of lithium-ion batteries, in terms of both efficiency and cycling life, depends critically on their thermal management [12,13]. A battery thermal management system (BTMS) is required in order to secure the desired performance of a battery or battery pack in a low-temperature environment and the desired lifetime in a high-temperature environment [14–16]. In addition, the temperature, which is an important factor, affects several

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Nomenclature

C	cell voltage or cell potential [V]
C_1	model constants
C_2	model constants
C_3	model constants
C_μ	constant
F	Faraday's constant (96,485 Columb/mol)
G_k	generation of turbulence kinetic energy due to the mean velocity gradients
G_b	generation of turbulence kinetic energy due to buoyancy
I	current [A]
k	turbulent kinetic energy (J)
L	characteristic dimension (m)
n	number of flow of electron
P	pressure (Pa)
Pr	Prandtl number
$\dot{Q}$	heat generation rate [W]
R	resistance (Ω)
Re	Reynold's number
S_k	user-defined source terms
S_ε	user-defined source terms
ΔS	change in entropy (J/K)
T	temperature [°C or K]
t	time [s]
V	speed (m/s)
v_s	mean fluid velocity (m/s)
$\overline{V}$	average velocity (m/s)
dE/dT	temperature coefficient [V/°C]
ω	turbulent eddy frequency (1/s)
y^+	enhanced wall treatment
Y_M	the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate

Greek symbols

∇	gradient operator
ρ	density (kg/m^3)
v	kinematic fluid viscosity (m^2/s)
μ	dynamic fluid viscosity (Ns/m^2)
λ	Reynold's stress
σ_k	turbulent Prandtl numbers for k
ε_k	turbulent Prandtl numbers for ε

Subscripts

act	actual
chg	charge
dis	discharge
n	negative
p	positive
sim	simulated

Superscripts

°	degree
+	Related to wall treatment

Acronyms

BEV	battery electric vehicle
BC	boundary condition
BTMS	battery thermal management system
C	capacity
CFD	computational fluid dynamics
EV	electric vehicle
FCV	fuel cell vehicle
FEM	finite element method
FSP	field synergy principle
HEV	hybrid electric vehicle
ICEM-CFD	popular proprietary software package used for CAD and mesh generation
LCC	liquid cooled cylinder
LabVIEW	laboratory virtual instrument engineering workbench
$LiMO_2$	lithium manganese oxide
$LiFePO_4$	lithium iron phosphate
LCC	liquid cooled cylinder
LCP	liquid cold plate
LPM	lumped parameter model
LPV	linear parameter varying
PC	personal computer
PCM	phase change material
PDE	partial differential equation
PHEV	plug-in hybrid electric vehicle
RNG	renormalization group
RANS	Reynolds-Averaged Navier-Stokes
SST	shear stress transport
TDR	turbulent dissipation rate
TKE	turbulent kinetic energy
2D	Two-dimensional
3D	three-dimensional

aspects of a lithium-ion battery, including the thermal and electrochemical behaviors, and ultimately performance and the cycle life cost [17–19]. A usual range of temperature is between 20 °C and 40 °C [20], and a prolonged range becomes between −10 °C and +50 °C for the allowable operation [21,22] for lithium-ion batteries. There are different methods of BTMS that include: (i) air cooling, (ii) water cooling, and (iii) phase change materials (PCM). The air cooling has attracted the attention of many researchers because of its simplicity [23] and light weight. The water cooling is more efficient method because of its ability to absorb more heat, as compared to air cooling, and it occupies less volume, but brings more complexities as well as high cost and weight [24–26]. In addition, because of the low thermal conductivity of air [27], higher air velocity is required to provide sufficient cooling of lithium-ion batteries using active cooling methods [28,29]. On the other hand, liquid cooling gives better cooling as compared to the air cooling due to their high thermal conductivities [30]. The example of a passive system is a PCM. In a passive system, the ambient air is used to carry the heat rejected by cells. The effective passive design avoids the use of components like fans, manifold, etc. [31,32].

In this research, the flow inside the cold plates is turbulent and therefore for turbulence model in ANSYS Fluent is used. The Reynolds number is used to determine the flow regime (laminar or turbulent) and was defined as shown in Eq. (1).

$$R_e = \frac{v_s L}{v} \tag{1}$$

where v_s is the mean fluid velocity (m/s), L is the characteristic dimension (m), v is the kinematic fluid viscosity (m^2/s), also defined as μ/ρ, and ρ is the fluid density (kg/m^3). In this study, $R_e = 8.7 \times 10^3$ and therefore the flow is considered turbulent.

The Reynolds-Averaged Navier-Stokes (RANS) based modeling approach, which averages the flow quantities for an entire range of scales of the turbulence being modeled, was employed. Two