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An investigation of lithium-ion battery thermal management using paraffin/porous-graphite-matrix composite

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HIGHLIGHTS

- A one-dimensional (1D) model using the thermal circuit method is proposed.
- The simplified 1D model agrees well with results from other methods.
- Phase change material (PCM) cooling proves better than forced convection.
- PCM improves the characteristics of the battery transient temperature rise.
- Design parameters to optimise the PCM cooling are investigated.

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ABSTRACT

The thermal management of a cylindrical battery cell by a phase change material (PCM)/compressed expanded natural graphite (CENG) is investigated in this study. The transient thermal behaviour of both the battery and the PCM/CENG is described with a simplified one-dimensional model taking into account the physical and phase change properties of the PCM/CENG composite. The 1D analytical/computational model yielded nearly identical results to the three-dimensional simulation results for various cooling strategies. Therefore, the 1D model is sufficient to describe the transient behaviour of the battery cooled by a PCM/CENG composite. Moreover, the maximum temperature reached by the PCM/CENG cooling strategy is much lower than that by the forced convection in the same configuration. In the test case studied, the PCM showed superior transient characteristics to forced convection cooling. The PCM cooling is able to maintain a lower maximum temperature during the melting process and to extend the transient time for temperature rise. Furthermore, the graphite-matrix bulk density is identified as an important parameter for optimising the PCM/CENG cooling strategy.

1. Introduction

The global efforts on reducing the carbon dioxide emission and the diminution of oil resources have made electric vehicle (EV) and hybrid electric vehicle (HEV) alternatives to the vehicle equipped with combustion engines. The requirements of battery power and capacity for HEV/EV vehicles have positioned Li-ion battery as the best candidate amongst various battery types, which has a better energy density and lower discharge rate compared to many other battery types. Nevertheless the performance of Li-ion battery is limited by temperature rise during the discharge process. Temperature affects strongly the safety, reliability and lifespan of the battery [1,2]. Efficient and safe running during driving operations is obtained by keeping the battery temperature between 20 °C and 40 °C [2]. Moreover, the temperature from cell to cell and module to module should be normally within 5 °C, for ensuring temperature uniformity. An uneven temperature distribution may lead to a short circuit in the battery. Consequent to these requirements, two types of cooling systems are used in the thermal management. One commonly used system is based on active cooling, using fluid flow for cooling the battery. Active cooling systems usually involve a bulky flow management, which increases the system mass and has the risk of fluid leakage. System components such as a pump are also required for moving the fluid. Besides, the cooling must be well distributed [3,4] in order to maintain an even temperature distribution in the entire pack.

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Nomenclature

Bi	Biot number
$[C]$	Matrix of the thermal capacitance [J K^{-1}]
c_p	Specific heat per unit mass [J kg^{-1} K^{-1}]
f	Transcendental function in the case of the PCM/CENG cooling
f_l	Liquid fraction of the PCM
$[G]$	Matrix of the conductance [W K^{-1}]
G_{conv}	Thermal conductance of convection [W K^{-1}]
h_r	Heat transfer coefficient in the radial direction [W m^{-2} K^{-1}]
h_z	Heat transfer coefficient in the axial direction [W m^{-2} K^{-1}]
J_0	Zero-order Bessel function of the first kind
J_1	First-order Bessel function of the first kind
k	Thermal conductivity [W m^{-1} K^{-1}]
L	Length of the cylindrical battery cell [m]
L_z	Half length of the battery cell [m]
l_f	Latent heat of fusion [J kg^{-1}]
$[P]$	Matrix of internal power [W]
q	Internal heat generation in the battery [W m^{-3}]
r_1	Position of the interface battery/CENG in the PCM/CENG cooling case [m]
r_2	Position of the external surface of the PCM/CENG composite in the radial direction [m]
R	Radius of the cylindrical battery cell in convection cooling case [m]
R_{conv}	Thermal resistance of convection [W K^{-1}]
$\tilde{R}_{i,n}$	nth eigenfunction of the ith solid in the radial direction for the PCM/CENG cooling
S_{conv}	Surface cooled in the radial direction in the PCME/CENG cooling [m^2]
T	Temperature [°C]
$[T]$	Matrix of the temperature [°C]
Y_0	Zero-order Bessel function of the second kind
Y_1	First-order Bessel function of the second kind

Greek letters

α_i	Thermal diffusivity of the ith solid
β_p	pth eigenvalue associated with the pth eigenfunctions $\tilde{\Phi}_p$
γ	Geometric ratio in the PCM/CENG cooling case
Δ	Variation
δ	Thermal diffusivity ratio in the PCM/CENG cooling case
ε	Porosity of the CENG graphite matrix
Θ_n	Time-variable function PCM/CENG cooling case
$\lambda_{i,n}$	nth eigenvalue associated with the nth eigenfunction $\tilde{R}_{i,n}$ in the PCM/CENG cooling
μ_n	nth eigenvalue associated with the nth eigenfunctions $\tilde{X}_n$
Π	Function defined by Eq. (32a)
ρ	Density [kg m^{-3}]
σ	Half width of the melting interval temperature [°C]
$\tilde{\Phi}_p$	pth eigenfunctions in the axial direction for the convection cooling case
φ_i	Time-variable function of the ith solid for the homogeneous equation in the PCM/CENG cooling case
$\phi_{1,n}$	Function defined by Eq. (31b)
$\tilde{X}_n$	nth eigenfunctions in the radial direction in the convection cooling case
$\Psi_{n,p}$	Time-variable function in the convection cooling case

Subscripts

adia	Adiabatic
Amb	Ambient
CENG	Compressed expanded natural graphite
comp	PCM/CENG composite
eff	Effective
g	Graphite (CENG)
H	Homogeneous
$i = 1,2$	Index number for the battery and the PCM/CENG composite respectively
m	Melting
Nconv	Natural convection
PCM	Phase change material
r,z	Cylindrical coordinates

Superscript

n	nth time step

An optimisation of the active cooling system can reduce its cost and size. Mohsen et al. [5] had optimised the air-cooling system for a cylindrical Li-ion battery pack using a genetic algorithm. However, the external surface of the battery had a constant temperature and the gradient in the battery was not analysed. Jarret and Kim [6,7] studied the optimisation of a cold plate subject to a constant heat flux and the impact of the boundary conditions on this optimum design, but the cold plate design was not considered in detail. Jin et al. [8] improved the design of a mini-channel liquid cold plate by applying oblique cuts in the straight line of the cold plate. This modification avoids the complete development of the hydrodynamic boundary layer responsible of the deterioration of the convective heat transfer in the straight line design. They also showed experimentally an enhancement of the performance with minimal penalty on the pressure drop.

Thermal management system should be compact, lightweight, reliable and low cost. As an alternative to active cooling, passive cooling systems based on phase change phenomena can be potentially advantageous. Heat pipes, based on the liquid/vapour phase change, were studied experimentally by Wu et al. [9]. They showed the importance of maintaining a good surface contact between the heat pipe and the battery. Based on this recommendation, Greco et al. [10] studied and designed the cooling system of a prismatic battery cell by a set of heat pipes embedded in copper material. A 1D computational model was developed and compared with an analytical approach and a three-dimensional (3D) computational fluid dynamics (CFD) simulation. It was demonstrated that the 1D model was sufficient to predict the temperature distribution of the lithium-ion battery. In addition to heat pipes, PCM based on solid/liquid phase change can be used for passive cooling, which has great a potential in reducing peak temperature during intermittent discharge and in overcoming performance losses at cold temperature. Duan and Naterer [11] investigated experimentally the behaviour of two PCMs during discharge under various environmental conditions. The PCMs allowed reducing the large temperature variations in the battery despite significant ambient temperature variations. In addition, the Stephan equation of the phase change problem in 1D was solved, where the solution described the propagation of the solid–liquid interface with a line heat source located in the centre. However, buoyancy effect was