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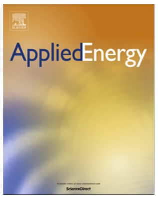

Numerical investigation of thermal behaviors in lithium-ion battery stack discharge

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HIGHLIGHTS

- The thermal behaviors of a Li-ion battery stack have been investigated by modeling.
- Parametric studies have been performed focusing on three different cooling materials.
- Effects of discharge rate, ambient temperature and Reynolds number are examined.
- General guidelines are proposed for the thermal management of a Li-ion battery stack.

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ABSTRACT

Thermal management is critically important to maintain the performance and prolong the lifetime of a lithium-ion (Li-ion) battery. In this paper, a two-dimensional and transient model has been developed for the thermal management of a 20-flat-plate-battery stack, followed by comprehensive numerical simulations to study the influences of ambient temperature, Reynolds number, and discharge rate on the temperature distribution in the stack with different cooling materials. The simulation results indicate that liquid cooling is generally more effective in reducing temperature compared to phase-change material, while the latter can lead to more homogeneous temperature distribution. Fast and deep discharge should be avoided, which generally yields high temperature beyond the acceptable range regardless of cooling materials. At low or even subzero ambient temperatures, air cooling is preferred over liquid cooling because heat needs to be retained rather than removed. Such difference becomes small when the ambient temperature increases to a mild level. The effects of Reynolds number are apparent in liquid cooling but negligible in air cooling. Choosing appropriate cooling material and strategy is particularly important in low ambient temperature and fast discharge cases. These findings improve the understanding of battery stack thermal behaviors and provide the general guidelines for thermal management system. The present model can also be used in developing control system to optimize battery stack thermal behaviors.

1. Introduction

Electric vehicles (EVs) nowadays become an alternative to replace internal-combustion-engine or fossil-fuel based power-train due to a significant advantage that the power (electricity) consumed can be generated from a wide range of sources, including fossil fuels, nuclear power, and renewable sources such as solar and wind power or any combination of those. Among a variety of batteries, Li-ion batteries have gained increasing attentions to be used in EVs, due to its high power density, long cycle-life and practical range of operating voltage [1].

However, the wide application and mass production of Li-ion battery are constrained by self-heating from entropy change and ohmic resistance even under a moderate charging and discharging rates [2], particularly in automotive applications with frequent charge/discharge cycles. Specifically, battery temperature influences the availability of discharge power for start-up and acceleration and the charge acceptance during energy recovery from regenerative braking, all of which affect vehicle drive-ability and energy conversion efficiency. The elevated temperature can cause the batteries to be ruptured, ignited or even exploded, which leads to reduced durability or permanent damage. Typically, mild

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Nomenclature

A	cross sectional area (m^2)
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
C	charge capacity (A h)
E_{oc}	open circuit voltage of the battery (V)
F	Faraday's constant; 96,458 ($C\ mol^{-1}$)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
I	current density ($A\ m^{-3}$)
i	discharge current (A)
k	thermal conductivity ($W\ m^{-2}\ K^{-1}$)
n	number of electrons transferred in reaction
q	heat generation rate per unit volume ($W\ m^{-3}$)
R/R_i	internal resistance ($\Omega\ m^3$)
S	entropy ($J\ mol^{-1}\ K^{-1}$)
SOC	state of charge
t	time (s)
T	temperature (°C)
$x/y/z$	spatial coordinate (m)
Re	Reynolds number
$\vec{v}$	velocity
P	steady-state pressure
μ	dynamic viscosity ($kg\ m^{-2}\ s$)
ρ	density ($kg\ \ m^{-3}$)

Subscripts

a	air
b	battery
0	initial condition

operations (avoiding fast and deep discharge that yield high temperature) prolong the battery life time. High degradation rate and thermal runaway have been observed under elevated temperature [3,4]. In addition, the internal ohmic resistance of the battery can be largely affected by temperature. For these reasons, effective thermal management is critical for Li-ion batteries to prevent operating beyond the optimum temperature range, and to balance cells to eliminate state of charge (SOC) mismatches [5] by achieving a uniform temperature distribution within the stack.

Mathematical modeling and simulation of heat transfer within the battery is an effective tool to obtain the working status and further guide the design and control of the system. A few numerical models for the Li-ion battery thermal management have been developed in previous studies. Karimi and Li [6] simulated the effect of cooling conditions and stack configuration on the temperature distribution, showing that a cooling strategy based on distributed forced convection is an efficient and cost-effective method. Maleki and Shamsuri [7] demonstrated the importance of thermal modeling and the accuracy of the selected methodology for computer battery-stack thermal management. Chen and Evans [8] developed a two-dimensional model of Li-ion batteries. By investigating the effect of component property and cooling condition on the performance, they proposed strategies to maintain the desired operating temperature. Subramannian et al. [9] derived a model from volume-average equations for the solid phase with the concentrated solution theory incorporated. The nature of the model and the structure of the governing equations are exploited to facilitate model reformulation, yielding efficient and accurate numerical computations. Such model based thermal analysis has been also conducted to study peer devices such as vanadium flow battery [10].

As to the empirical models, Smith et al. [11] developed an electrical–thermal coupled model of a single Li-ion cell and a module with 16 cells in parallel. Equivalent electrical and thermal circuits were integrated into their module-level model, and the modeling results were used to assess the battery thermal safety margin. Giuliano et al. [12] developed a method to determine the entire surface temperature field of a lithium-titanate cell. The resulting temperature measurements were used to evaluate the effectiveness of an active cooling system while exhibiting the least parasitic losses. Mills and Al-Hallaj [13] designed a passive thermal management system with a graphite impregnated phase change material (PCM) for a Li-ion battery stack based on modeling results. Kizilel et al. [14] and Duan and Naterer [15] studied the thermal behaviors of the battery stack with PCM cooling system under various conditions.

At present, the cooling of EVs can be divided into three major categories: air cooling, liquid cooling and phase change material cooling. There are a few prior works discussing these three cooling techniques. Sabban et al. [16] investigated the features of temperature increase and uniformity of temperature distribution from the air cooling and PCM cooling. Their simulation was compared with experimental results focusing on the effectiveness of active cooling and passive cooling for the thermal management of a battery stack. Kizilel et al. [14] demonstrated the advantage of using the novel PCM thermal management systems over conventional active cooling systems. Although the temperatures of these two cooling methods were compared, the underlying reasons for such difference are not disclosed in details.

The abovementioned work either focuses on the thermal behaviors of a single battery or a specific cooling material/method. A comprehensive investigation of different cooling strategies/materials as to their influences on the thermal behaviors of a battery stack system still lacks. This paper presents our attempts in this direction. In our prior work [17], we have developed both numerical and analytical models to study the effects of cooling channel and battery stack geometries on battery thermal management. The present work is a continuation which turns the focus to the battery operating conditions. Specifically, we aim to investigate the effects of a few important operating parameters, including discharge rate (C-rate), Reynolds number and ambient temperature, on the thermal management with three typical cooling materials. The objective is to understand and develop the general guideline to choose the appropriate cooling materials and operating strategies under different conditions. Parametric study based on numerical simulation is an effective approach for this purpose.

2. Model development

2.1. Physical problem

Li-ion batteries can be designed into different shapes such as cylindrical, coin, prismatic, and thin and flat, with their individual advantages and scope of application. In EV applications, the flat-plate and cylindrical designs are often preferred with relatively higher power density. The trade-off between these two designs has been discussed in our prior publication [17]. In this study, we choose the flat-plate battery stack to perform the parametric study.

Fig. 1 is a schematic of a 20-battery stack connected in series using the flat-plate design. With a dimension of 16 cm in width and 25 cm in height, each battery is comprised of 10 pieces of shunt-wound single cell, producing a total capacity of 20 A h. All thermal and physical properties of battery components are summarized in Table 1. Two sets of cooling channels are built on