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Nanofluid-based cooling of cylindrical lithium-ion battery packs employing forced air flow

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ABSTRACT

Efficient cooling strategies are very important issues in thermal management of lithium-Ion battery system and these techniques should provide cost effective and energy saving solutions for temperature rise of the system during battery operation. A pseudo 2D electrochemical model has been used to investigate the electrochemical and thermal condition of commercial 18650 Lithium-Ion battery. This analysis was compared to previous experimental studies and results showed that the model predicts the temperature rise and thermal power generation very well. Results from the electro-thermal analysis were used to examine a cooling method. In this strategy, the cylindrical Li-ion cell is submersed within a thin cylindrical tank containing water-Al_2O_3 nanofluid. Air flow is employed to remove the heat from the system during discharge process. After testing this method for a single cell with various sizes of the secondary cylinder, critical and thermally dangerous arrangements of Li-ion cells were analyzed employing the new technique. 3D transient Computational Fluid Dynamics (CFD) simulations were used to see the effect of presence of the secondary cylinder on temperature rise. Results revealed that the new method reduces the maximum temperature of the cells efficiently.

1. Introduction

Due to extensive usages in many electronic devices and transport industry [1,2], Li-Ion battery is a valuable designation in the application of large battery systems [3]. Therefore, Battery Management System (BMS) has attracted extensive considerations in recent years [4–7]. However, there are some important limitations for employment of such batteries. Local temperature enhancement in Li-ion battery packs leads to devaluation of cycle life and may cause to thermal runaway of the cell/pack. It is needed for such important issue to assign efficient thermal management as it is critical as well as challenging [8–10]. Not only temperature restriction of 0 °C–40 °C, but also heterogeneous and uneven temperature distribution in the cells are the major technological hindrance and difficulty [11–14]. Hence, indispensable efforts should be paid for the battery thermal management system to keep the temperature below the dangerous limitation and amend the consistency and safety of lithium-ion batteries [15,16].

Various strategies have been used for battery thermal management which can be classified into different types [8,17–20]. Using air as coolant, employment of liquids as coolant and applying Phase Change Materials (PCM) as cooling medium. Among these coolants, air is the most commonly used due to its simple needed supplies and trustworthy system operation. For high rate discharges, when the temperature rises extremely, using air as coolant may not be reasonable [21]. In this condition, liquid cooling may be efficient and it can be achieved through submerging modules in a dielectric fluid for direct contact, or placing the modules on a liquid cooled plate (heat sink) [22–27]. Employing mentioned mechanisms with liquid cooling as described in Ref. [22] seems to be more difficult and complicated rather than air cooling. Liquid pump and liquid/air or liquid/liquid heat exchanger are the main components of the liquid cooling systems. Keeping the cell temperature stable, temperature rise of the module is stored as latent heat in the PCM [28,29]. Hallaj and Selman [30] suggested this strategy and then it received many efforts and attention from researchers [31,32]. Although the two last mentioned methods are very useful and reduce the temperature efficiently, by considering many other parameters such as manufacturing cost, parasitic energy loss, full

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battery system weight, removal of potentially hazardous gases, and layout limitation, air cooling seems to be widely employed method [33–42]. Therefore, many researchers have studied the air cooling strategy for Li-Ion pack to control the temperature rise.

Studies about performance of various air flow duct modes, employing metal-foam based heat exchanger plates, gapspacing and air flow rate were conducted by many researchers and valuable results obtained for thermal management of the Li-Ion pack [43–45]. Mahamud and Park [15] suggested a novel battery thermal management strategy employing reciprocating air flow with 2D Computational Fluid Dynamics (CFD) and lumped capacitance thermal model for battery cells. Wang et al. [46,47] carried out 3D unsteady numerical experiments to find out the suitable arrangement of modules within a pack. They found out that a 5 × 5 Li-Ion pack has better thermal performance rather than other module distributions. Moreover, different places of the fan for air cooling were discussed for battery box.

Xunet al. [48] investigated the influence of the cooling channel scheme on the thermal performance of both the flat-plate and the cylindrical battery packs during discharge. Fan et al. [45] studied the effect of various cooling channel layouts on the thermal performances for a prismatic lithium-ion battery module. Yang et al. [49] developed a physical thermal model coupled with the governing equations of fluid flow for the lithium-ion battery pack and the cooling performances between the staggered and aligned cell arrangements, the temperature distribution, maximum temperature rise, fan power, and cooling index were studied for different cooling designs. An optimized scheme was finally presented for the cylindrical battery pack.

In this study, we analyzed the thermal management of 18650 Lithium-Ion module and battery pack when submersing the cells into a secondary thin cylinder filled with water-Al_2O_3 nanofluid. For this direct contact of liquid to the cell, no circulation of cooling liquid is needed and air is flowing as the working fluid to remove the generated heat. After selection of secondary cylinder size, various arrangement of Li-Ion pack is tested to examine the efficiency of the current strategy. Pseudo 2D electrochemical model was compared with experimental results and then the model was used to assess the cooling method employing CFD.

2. Mathematical model

2.1. Electrochemical model

2D electrochemical model of Li-Ion cell is schematically illustrated in Fig. 1. Geometrical dimensions of different parts of the cell, such as the current collector, electrodes, separator and other electrical parameters are shown in Table 1 [47,48]. During charging operation, Li ions are removed from positive electrode and are moved into the negative electrode. Reverse direction will be taken for discharging operation. Temperature of different points including cell inside and outside are increased during these operations. The related reactions are defined as follow:

$$LiC_6 \overset{Charge}{\leftarrow} \xrightarrow{Discharge} Li_{1-x}C_6 + xLi^+ + e^- \tag{1}$$

$$xLi + xe^- + Li_{1-x}FePO_4 \overset{Charge}{\leftarrow} \xrightarrow{Discharge} LiFePO_4 \tag{2}$$

Modeling the electrodes, porous electrode theory is used including active materials and electrolyte which are evaluated as superimposed with own volume fraction of ε_s and ε_l, respectively. Considering the porosity and tortuosity effect, Bruggeman factor was employed to correct electrolyte diffusion, electrolyte conduction and electrical conductivity in the electrode as below [50,51]:

$$D_{l,eff} = \varepsilon_l^{3/2} D_l, \quad \sigma_{l,eff} = \varepsilon_l^{3/2}\sigma_l, \quad \sigma_{s,eff} = \left(1 - \varepsilon_l - \varepsilon_f\right)^{3/2} \sigma_s$$

According to the Ohm's law in the electrode, the current density and charge balance are described as below [50,51]:

$$i_s = \sigma_{s,eff} \nabla \varnothing_s \tag{3}$$

$$\nabla . i_s = j \tag{4}$$

where transfer current value is [50,52,53]:

$$j = \begin{cases} a_{s,a} i_{ioc,a} \\ 0 \\ a_{s,c} i_{ioc,c} \end{cases}, \quad \text{In the negative electrode} \tag{5}$$

$$i_{ioc} = i_0 \left\{ exp\left[\frac{\alpha_a F}{RT}(\eta)\right] - exp\left[-\frac{\alpha_c F}{RT}(\eta)\right] \right\}, \quad \text{In the separator} \tag{6}$$

$$i_0 = F(k_c)^{\alpha_a}(k_a)^{\alpha_c}(C_{s,max} - C_s)^{\alpha_a}(C_s)^{\alpha_c}\left(\frac{C_1}{C_{l,ref}}\right)^{\alpha_a}, \quad \text{In the positive electrode} \tag{7}$$

There exists very thin film around solid particles can be treated as loss, namely Solid Electrolyte Interface (SEI). Additional variable for potential measurements was used, so [52]:

$$\varDelta \varnothing_{s,SEI} = i_{ioc} R_{SEI} \tag{8}$$

Additional potential for the operation of overpotential is written as [52].

$$\eta = \varnothing_s - \varDelta \varnothing_{s,SEI} - \varnothing_l - E_{eq} \tag{9}$$

Knowing that State of Charge (SOC) and temperature describes the equilibrium potential, and employing Taylor's first expansion, we can write [51]:

$$E_{eq} = E_{0,ref} + \left(T - T_{ref}\right) \frac{\partial E_{eq}}{\partial T} \tag{10}$$

For present analyses, related voltage of open circuit [54] and [55] electrodes at 25C are defined by Eqs. (11) and (12), respectively:

$$\begin{aligned} E_{eq,c} = {} & 2.567462 + 57.69[1 - \tanh(100z + 2.9163927)] \\ & + 0.442953\ tan^{-1}(-65.41928z + 64.89741) \\ & + 0.097237\ tan^{-1}(-160.9058z + 154.590) \end{aligned} \tag{11}$$

$$\begin{aligned} E_{eq,a} = {} & 0.6379 + 0.541\ \exp(-305.5309z) + 0.044\ tanh[\\ & -(z - 0.1958)/0.1088] \\ & - 0.1978\ tanh[(z - 1.0571)/0.0854] \\ & - 0.06875\ tanh[(z + 0.0117)/0.0529] \\ & - 0.017\ tanh[(z - 0.5692)/0.0875] \end{aligned} \tag{12}$$

Eq. (13) represents conservation of charge for the electrolyte part [53]: