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Research Paper

Prevent thermal runaway of lithium-ion batteries with minichannel cooling

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HIGHLIGHTS

- A 3D model was developed to study nail penetration induced thermal runaway.
- Effects of flow rate, thermal abuse reactions, and nail dimensions were examined.
- Minichannel cooling at cell level cannot cease thermal runaway in a single cell.
- Minichannel cooling can prevent thermal runaway propagation between cells.

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ABSTRACT

Thermal management on lithium-ion batteries is a crucial problem for the performance, lifetime, and safety of electric vehicles (EVs) and hybrid electric vehicles (HEVs). Fire and explosions can be triggered by thermal runaway if the temperature of the lithium-ion batteries is not maintained properly. This work describes a minichannel cooling system designed at the battery module level and the investigation on its efficacy on the mitigation of thermal runaway. Nail penetration was employed to simulate the internal short circuits, which in reality may be caused by vehicle collisions and/or manufacturing defects. Two integrated models were utilized to study thermal runaway: the conjugate heat transfer model and the reaction kinetics model. Numerical simulations were conducted to understand the thermal runaway process and the effects of flow rate, thermal abuse reactions, nail penetration depth, and nail diameter. It is concluded that minichannel cooling at cell level cannot cease thermal runaway in a single cell, but it can prevent battery fratricide due to thermal runaway propagation between cells.

1. Introduction

The rapid emergence of various electric vehicles (EV) and hybrid electric vehicles (HEV) around the world has created an urgent demand for high-performance batteries at low cost. Lithium-ion batteries are commonly used in EVs, due to their high energy density [1–3]. Their lifetime, performance, and safety are largely influenced by the operating battery temperature [4–6]. At a temperature below the desired range (15–35 °C [7]), battery performance will be lowered due to poor ion transport. At a temperature higher than 35 °C, side reactions happen faster, which leads to higher loss rates of cyclable lithium and active materials [7]. Many thermal management methods, e.g., air cooling [8–14], refrigerant cooling [15,16], liquid cooling [13,17–19], and phase change material (PCM) cooling [20–23], have been investigated. Though a few thermal management schemes are being applied in commercial electric cars (e.g. air cooling: Toyota Prius, Nissan Leaf; refrigerant cooling: BMW i3; and liquid cooling: Tesla Model S, Chevy Volt), after and more cost-effective thermal management methods are still desirable, especially in extreme environments or under abuse conditions that would otherwise lead to a fire or explosion [24–26].

When the temperature of a lithium-ion battery is elevated and the heat can't be dissipated effectively, thermal runaway due to the exothermic reactions can occur [2,25,26]. Thermal runaway involves a rapid temperature increase, release of gas, smoke, fire, and an explosion. There are numerous external and internal abuse conditions that can cause thermal runaway, e.g., external heating, over charging/discharging, nail penetration, and external short [27]. Among them, nail penetration is often used to simulate the internal short circuit in a cell [28,29], analogue to the internal shorting resulted from car collisions or manufacturing defects such

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Nomenclature

A	surface area of the inserted nail (mm^2)
a	frequency factor (1/s)
c	dimensionless concentration
c_p	specific heat (J/kg K)
E	activation energy (J/mol)
H	heat release during thermal abuse (J/kg)
h	height of the minichannel (mm)
h_{conv}	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	depth of nail penetration (mm)
P	pressure (Pa)
ΔP	total pressure drop across the minichannel system (Pa)
$\dot{q}_{conv}$	convective heat transfer at the cell boundaries (W/m^2)
$\dot{q}_{rad}$	radiative heat transfer at the cell boundaries (W/m^2)
Q	pumping power (W)
R	the gas constant, 8.314 (J/mol K)
r	radius of the nail (mm)
S	heat generation during nail penetration (W/m^3)
T	temperature (K)
t	time (s)
$\vec{u}$	velocity (m/s)
V	volume of the inserted nail (mm^3)
$\dot{V}$	volumetric flow rate (m^3/s)
W	specific content in jellyroll (kg/m^3)
w	width of the minichannel (mm)
z	dimensionless solid electrolyte interface (SEI) thickness
α	degree of conversion
ε	emissivity of the battery surface
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant, 5.67e−8 (W/m^2 K^4)
μ	dynamic viscosity (kg/m s)
δ	thickness of aluminum between the outer surface and the minichannel (mm)

Subscripts

abuse	thermal abuse
amb	ambient
b	battery
e	electrolyte
n	nail
ne	negative-electrolyte
pe	positive-electrolyte
sei	solid electrolyte interface
sur	battery boundaries
w	water

as a conductive particle wound in the jelly roll. It has been commonly believed that during the nail penetration process, short circuit occurs first between adjacent electrode pairs, which generates a huge amount of heat and increases the battery temperature. When the battery temperature reaches a threshold (~120 °C), the decomposition of battery materials (referred to as thermal abuse) takes places, which further accelerates the heat generation [30,31]. Hatchard et al. [32] conducted oven exposure tests for cylindrical and prismatic Li-ion cells, and developed a 1D modeling approach to calculate the reaction kinetics for thermal abuse. This modeling method was then extended by Kim et al. [33] to 3D so that the geometrical features of the battery could be considered. Zhao et al. [34] used a 3D multiscale electrochemical-thermal model to conduct a parametric study of the nail penetration process in a large-format li-ion cell. Using this model, they analyzed the effects of nail diameter, nail conductivity, and cell capacity on the cell behavior.

As the thermal runaway is triggered in a single cell, it may propagate to adjacent cells if no appropriate measurement is used to prevent it. The thermal runaway propagation could result in a severe thermal hazard, and therefore, should be considered in battery thermal management design [35]. At present, however, only limited experimental and computational studies have been conducted to study the mechanism during this propagation process. To the best knowledge of the authors, the only experimental study in literature was conducted by Feng et al. [29]. They investigated the penetration induced thermal runaway propagation within a 6-battery module. The first battery of the module was penetrated to trigger the thermal runaway. Their results showed that 12% of the total heat released in thermal runaway could trigger the thermal runaway of the adjacent battery. Yang et al. [36] developed a 3D electrochemical-electrical-thermal model using National Renewable Energy Laboratory (NREL)'s Multi-Scale-Multi-Dimensional (MSMD) modeling approach to identify the characterization of thermal runaway propagation in a li-ion battery module. Chen et al. [37] implemented a coupled electro-thermal model in COMSOL Multiphysics to study the influence of the overheated cylindrical battery cell on surrounding batteries in the 7×3 battery module. Only the convective and radiative heat transfer on the battery surface was used to dissipate the heat generated in the batteries. Their results showed that thermal runaway can be induced in other adjacent cells within a 3 mm distance of the overheated cell if the accumulated heat could not be dissipated sufficiently rapidly.

In this study, a novel minichannel cooling system was developed for the thermal management of the lithium-ion battery module. The minichannel design features multiple aluminum multi-port extrusions. Coolant will flow through the minichannels and absorb the heat from the batteries. This design has the advantage of high efficiency, light weight, and low cost. Our goal is to investigate the characteristics of nail penetration induced thermal runaway with the assist of the minichannel cooling system at the battery cell level and battery module level. The feasibility of using minichannel cooling to prevent thermal runaway in one battery cell and thermal runaway propagation from one cell to adjacent cells is also analyzed.

2. Model description

2.1. Physical problem

The novel minichannel cooling system is designed based on a battery module with five prismatic cells, as shown in Fig. 1. The dimensions of each cell are 180 mm (height) by 130 mm (width) by 50 mm (depth), and the capacity is 55 Ah. Three of the five cells are wrapped by aluminum minichannels. The geometric details of the minichannel are shown in Fig. 2. The height of channel is $h = 3$ mm, and width is $w = 3$ mm. The thickness of aluminum between the outer surface and channel is $\delta = 1$ mm, and the thickness between two neighbor channels is 2δ [1,38]. This particular minichannel geometry is adopted from a typical extruded multi-port aluminum tube. The changes to the geometry will have impact on its performance. For example, if the channel height (h) is reduced while other parameters remain the same, the liquid flow rate will increase and therefore the minichannel system will have