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Research Paper

Experimental investigation on lithium-ion battery thermal management based on flow boiling in mini-channel

Zhoujian An, Li Jia *, Xuejiao Li, Yong Ding

Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
Beijing Key Laboratory of Flow and Heat Transfer of Phase Changing in Micro and Small Scale, Beijing 100044, China

HIGHLIGHTS

- A new type of BTM system based on flow boiling in mini-channel are presented.
- Uniform temperature and volume distribution of battery module are obtained.
- The temperatures of battery cell are maintained around 40 °C.
- There exists an appropriate *Re* number range for boiling heat transfer in mini-channel.

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ABSTRACT

In order to guarantee the safety and prolong the lifetime of lithium-ion power battery within electric vehicles, thermal management system is essential. A new type of thermal management system based on flow boiling in mini-channel utilizing dielectric hydrofluoroether liquid which boiling point is 34 °C is proposed. The cooling experiments for battery module are carried out at different discharge rates and flow *Re* number. The cooling effect and the influence of battery cooling on the electrochemical characteristics are concerned. The experimental results show that the thermal management can efficiently reduce maximum temperature of battery module and surface maximum temperature difference. A relatively uniform temperature and voltage distributions are provided within the battery module at higher discharge rate benefit from the advantage of boiling heat transfer with uniform temperature distribution on cold plate. It is shown that the voltage decreases with the increase of *Re* number of fluid due to the reducing of temperature. There exist slight fluctuations of voltage distribution because of the non-uniformity of temperature distribution within the battery module at higher discharge rates. For different discharge rate, there also exists an appropriate *Re* number range during which the mode of heat transfer is mainly in boiling heat transfer mode and the cooling result can be greatly improved.

1. Introduction

With social progress and economic development, global energy shortage and environmental pollution problems have become increasingly prominent. In transportation sector, Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs) have been widely appreciated because of higher energy utilization efficiency and greater energy saving potential. At the same time, electric energy can be obtained through renewable energy, such as solar energy and wind energy, which can effectively mitigate environmental pollution problems [1].

For EV and HEV, battery is the most important factor constraining the performance and development. Lithium-ion power battery has become the main choice for EV and HEV energy supply due to the potential of higher energy density, higher power density, lighter weight, no memory effect, and lower self-discharge rate, longer calendar and cycle life when compared to other rechargeable battery types [2,3].

Heat is generated during battery charging and discharging due to the effects of chemical reaction and internal resistance, which leads to battery temperature increasing. Lifespan, safety and ageing rate are closely related to operating temperature at the same time [4–6]. Waldmann et al. [4] found that cells exhibited the slowest ageing for T = 25 °C in the range of −20 °C to 70 °C. Below

* Corresponding author at: Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China.

E-mail address: ljia@bjtu.edu.cn (L. Jia).

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25 °C, the ageing rates increased with the decrease of temperature. While above 25 °C the ageing was accelerated with the increase of temperature. It just showed different ageing mechanisms. Ramadass et al. [7] also reported that capacity fading of lithium-ion battery could be accelerated with the increase of operating temperature (25 °C, 45 °C, 50 °C, 55 °C). However, at higher temperatures (<60 °C) the power capability of lithium-ion cells increased with the increase of temperature [8]. To balance the power capability and ageing rate, lithium-ion batteries operate best at temperatures between 25 °C and 40 °C [9]. Furthermore, overheating can give rise to the occurrence of thermal runaway when the heat in a battery pack is not dissipated properly [10]. It is indicated that battery thermal management (BTM) is a key safety issue for the high-power lithium-ion battery pack.

Different type of BTM system can be classified as air cooling, heat pipe cooling, phase change material (PCM) cooling and liquid cooling [11].

Air cooling technology is one of the most commonly employed battery cooling approach, and widely used in electronics and vehicles because of the advantage of low cost and simple equipment [12–14]. Liu et al. [12] presented a shortcut computational method to estimate the flow temperature profiles for a parallel airflow-cooled large battery pack. A collective adjustment of operating parameters was provided to maintain the maximal temperature difference below 5 °C. Tong et al. [13] numerically analyzed the effect of certain design and operating parameters of the thermal management system on the performance of the battery module. They found that both increase of the inlet air velocity and decrease of the distance between the cells can effectively decline the temperature increasing. But the cooling capacity is limited because of the low thermal conductivity and specific heat of air especially for battery pack operating in high ambient temperature.

Based on the large amount of latent heat of liquid during vaporization, some researchers studied the BTM system based on heat pipe [15–17]. For instance, Ye et al. [15] proposed an optimized heat pipe thermal management system (HPTMS) for fast charging lithium-ion battery cell/pack. Experimental results and transient simulation of HPTMS integrated with batteries charged at different rates showed that the improved HPTMS could cater for lithium-ion batteries charged at high rate (up to 8 C rate). However, the numerical simulations also shown that the finned HPTMS with forced air convection at the condenser sections may be effective at the unit level but not at the battery pack level. It should be attributed to the low specific heat capacity of air.

Due to a large amount of heat can absorb during the process of solid-liquid phase change, PCM is also the excellent candidate for BTM. Javani et al. [18], Wang et al. [19] and Babapoor et al. [20] studied the BTM system based on pure PCM, paraffin/aluminum foam composite PCM and carbon fiber composite PCM respectively, and all these BTM systems showed a better performance on controlling the temperature of batteries. As pointed out by Mohammadian et al. [21], PCM as passive cooling method would be ineffective in the long run because of completely melting of PCM.

As a traditional form of cooling method, liquid cooling (liquid flowing and boiling) has become the most efficient and common cooling technology. For EV and HEV, Pesaran [22] showed that liquid cooling can get a better cooling effect, although the system is more complex than that of air cooling. Generally, the liquid cooling can be categorized into two different types. One is using pipeline, cold plate or jacket to separate liquid from the battery, and the heat is transferred to working fluid by conduction and convection or flow boiling to achieve the purpose of cooling the battery [23–26]; the other is that the battery is directly immersed in a dielectric [27–29].

Jin et al. [23] developed a simple configuration of oblique cuts across the straight fins of a conventional straight channel design, to enhance the performance of the conventional channel with minimal pressure penalty. Experimental results showed that heat transfer coefficients of oblique mini-channel were higher than those of conventional straight mini-channel, and the temperature uniformity on the heat source of the oblique fin cold plate was better than that of the conventional straight channel cold plate. Bandhauer and Garimella [24] proposed a passive, internal thermal management system for batteries using micro-scale liquid-vapor phase change to reduce thermal gradients inside the battery for improving safety and durability.

At present, the working fluids for battery cooling mainly include mineral oil [22], refrigerant [24], water [25,26] and glycol [29]. For BTM system based on liquid cooling, short circuit which resulted from liquid leakage is a significant security risk if the working fluid is not dielectric. NOVEC 7000 is kind of dielectric coolant, and also is stable at high temperature, non-flammable and environmentally friendly. The boiling temperature of NOVEC 7000 is 34 °C at 1 atmosphere, which is within the optimal operating temperature range for lithium-ion battery, namely 25–40 °C. A new battery temperature control system, "Boiling Liquid Battery Cooling" was developed by Hirano et al. [27]. It was revealed that the maximum temperature of the battery pack (ten 1 A h battery cells in series) was able to be kept around 35 °C even at a discharge rate as large as 20 C. Compared with single phase convection heat transfer, flow boiling heat transfer has higher heat transfer coefficient, and allows for lower temperature rise in the cells.

Although plenty of scholars have carried out experimentally research on the BTM, these almost based on single battery, little for battery module or pack. For battery module/pack, the maximal temperature and the temperature uniformity throughout the pack should be concerned. Cells running at difference temperatures in a pack can cause electrochemical imbalance over time. When cells in the module operate at different temperatures, each cell is charged and discharged slightly differently during every cycle, which will lead to difference in the state of charge between different cells. This will be amplified with the long term operation. Therefore, an appropriate BTM system for battery pack is necessary to ensure the batteries working within a safe temperature range and having better temperature uniformity among the batteries and improve the voltage distribution uniformity.

As mentioned above, it is a challenge to control the temperature of battery pack at an optimal temperature range and ensure the electrochemical performance, especially for higher discharge rate and thermal runaway. In this paper, a novel cooling method based on flow boiling in mini-channel was proposed. The effects of several important operating parameters, such as mass flow rate and discharge rate on the thermal management performance were investigated. The temperature distribution and voltage distribution within the battery module were emphatically analyzed. The purpose was to reveal the thermal management performance of the proposed cooling method for large-scale battery pack and develop guideline for thermal management system design.

2. Experimental setup

2.1. Flow loop

The schematic diagram of the flow loop is illustrated in Fig. 1. A peristaltic pump was used to circulate coolant in the closed-loop system, and the sub-cooler and preheater after the pump were installed to adjust the inlet temperature of coolant by controlling the cold water flow rate and heating power. A Coriolis-type mass flow meter was arranged between the sub-cooler and preheater for accurately measuring the mass flow rate. Pressure sensors and temperature transmitters were attached to the manifolds