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Experimental investigation on using the electric vehicle air conditioning system for lithium-ion battery thermal management

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ABSTRACT

It is investigated a lithium-ion battery thermal management (BTM) system using the electric vehicle (EV) air conditioning refrigerant to cool the battery pack directly. In the system, basic finned-tube heat exchanger structure and a special aluminum frame are adopted to design the battery pack thermal management module with lithium-ion batteries of cylindrical shape. The module is then integrated into the electric vehicle air conditioning system using two electronic expansion valves for the automatic control of the pack's temperature with self-programmed control software. Experimental results show that the BTM system can control the battery pack's temperature in an appropriate preset value easily under extreme ambient temperature, as high as 40 °C. In addition, through the refrigerant circuit optimization it can reduce the temperature non-uniformity inside the battery pack. The temperature difference within the pack is less than 4 °C in the constant discharge rate of 0.5 C, 1 C, 1.5 C laboratory tests, and 1.5 °C in road drive tests.

Introduction

Lithium-ion batteries are widely used in electric vehicles (EVs) due to their high discharge volt, and high energy/power density (Jaguemont, Boulon, & Dube, 2016). However, lithium-ion batteries must be strictly kept within a temperature range to have an appropriate performance. Overheating will severely undercut, among others, their power and life cycle (Ianniciello, Biwolé, & Achard, 2017). It has been found that the lifespan for a lithium-ion cell is reduced by approximately two months for every degree of temperature rise, while operating in a temperature range of 30–40 °C (Banzinski & Wang, 2015). In addition, the capacity and power of lithium-ion batteries will decay with higher operating temperature. Higher is the temperature, more severe it will be the reduction of the battery capacity (Xia, Cao, & Bi, 2017). Moreover, a lithium-ion battery generates a considerable amount of heat during its operation. Panchal, Dincer, Agelin-Chaab, Fraser, and Fowler (2016a) investigated the impact of various discharge rates on the thermal and electrical performance of a 20 Ah Li-ion phosphate battery. The test results showed that the battery surface temperature quickly increases for all C-rates. (C-rate means current-rate, which is defined as the charge or discharge current divided by the nominal capacity of battery.). The same research group also tested the battery heat generation at different discharge rates and under dual cold plate liquid cooling (Panchal, Dincer, Agelin-Chaab, Fraser, & Fowler, 2016b). The results showed that the highest rate of heat generation was found to be 91 W for 4 C discharge rate and when the cold plate was at 5 °C while the minimum value was 13 W measured at 1 C discharge rate and when the cold plate was at 35 °C. If no effective thermal management is in place, the battery will overheat and thermal runaway may occur causing it to burn or even to explode with serious safety consequences for EV (Feng, Ouyang, Liu, Lu, & He, 2018). It is desirable for lithium-ion batteries to be kept within the temperature range of 25–35 °C and a temperature difference within a pack below 5 °C (Ianniciello, Biwolé, & Achard, 2017; Ye, Saw, Shi, & Tay, 2015). Therefore, it is crucial for lithium-ion batteries having an effective thermal management.

Depending on the heat extraction system, the battery thermal management (BTM) can be divided into four types, namely: 1) air; 2) heat pipe; 3) PCM; and 4) liquid cooling/heating (Wang, Jiang, Li, & Yan, 2016). Air-cooling/heating systems are a convenient method for BTM because air has low density and viscosity, a stable chemical composition, easy flow control and low cost. Therefore, air-cooling/heating systems have been commonly used in EV (Chen, Song, Wei, & Wang, 2018). He and Ma (2015) investigated the thermal management of a Li-ion battery module consisting of multiple cells employing active temperature control and cooling/heating counterflow. In comparison with the results with passive control or parallel cooling/heating flow, temperature non-uniformity for the entire module was reduced from 4.2 to 1.0 °C. In addition, the required flow rate for counterflow was reduced by 38% as compared to the parallel flow arrangement. Yang, Zhang, Li, and Hua (2015) conducted a comparative analysis of the thermal performance for different arrangements of cylindrical cells for a $LiFePO_4$ battery pack. They discussed the effect of the longitudinal

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and transverse spacing on the cooling performance of a cylindrical battery pack for both aligned and staggered cell arrangements and obtained a reasonable design of the cooling/heating system for the aligned arrangement of the battery pack. However, airflow cooling becomes increasingly difficult when the environment temperature increases, due to the low specific heat of air, which requires very high flow rates to achieve appropriate heat removal rates.

Numerous researchers have used the heat pipe for the purpose of BTM. For example, Wang et al. (2015) provided a full experimental characterization of heat pipe battery cooling/heating covering a range of battery 'off-normal' conditions. Their investigation results show that the proposed method is able to keep the battery surface temperature below 40 °C if the battery generates less than 10 W/cell heat, and it can reduce the battery temperature down to 70 °C under uncommon thermal abuse conditions (e.g. 20–40 W/cell heat generation). Ye, Shi, Saw, and Tay (2016) incorporated heat pipes into a thermal management system for prismatic or pouch cells. The investigation results confirm that the system is feasible and effective for fast charging lithium-ion battery packs. Wu, Yang, Zhang, Chen, and Wang (2017) designed a heat pipe-assisted phase change material (PCM) based battery thermal management system to fulfill the comprehensive energy utilization for electric vehicles and hybrid electric vehicles. The experimental results show that with forced air convection, the highest temperature could be controlled below 50 °C even under the highest discharge rate of 5 C and a more stable and lower temperature fluctuation is obtained under cycling conditions. Liang, Gan, and Li (2018) investigated a heat pipe (HP) based BTM strategy by taking into account the effect of coolant flow rate, ambient temperature, coolant temperature and HP-BTM start-up time. Their results show that the thermal performance of a BTM system can be enhanced by cooling strategies. Although HP-BTM needs no additional power to circulate coolant in battery pack, it still needs the effective cooling of the condensation section of the heat pipes for the normal BTM operation. In addition, heat pipes are relatively with a high cost.

PCM can absorb or release large latent heat during phase change to cool or heat battery pack. Javani, Dincer, Naterer, and Yilbas (2014), Wang, Zhang, Jia, and Yang (2015), and Jiang, Huang, Fu, Cao, and Liu (2016) investigated for the purpose of BTM using PCM, metal foam/PCM composite and expandable graphite, respectively. The results indicate that BTM based on PCM can control the battery temperature effectively. However, PCM cannot cool or heat battery pack effectively when the battery pack operates for an extended period and all PCM is already molten.

BTM liquid cooling/heating, due to high heat transfer coefficients, can fulfill the requirements for effective thermal management of the battery pack, when it is in fast discharging mode or after extended operation. Generally, liquid cooling/heating BTM can be classified as active or passive, whether there is additional equipment or not to cool/heat the working fluid (Wang, Jiang, Li, & Yan, 2016). Yang, Tan, and Liu (2016) proposed a liquid metal as a new kind of coolant to be used for BTM. Their numerical simulation results show that compared to water, the liquid metal improved the module thermal performance in terms of the temperature level and uniformity, and it required less pump power consumption. Mondal, Lopez, and Mukherjee (2017) proposed the use of nanofluids, which are colloidal suspensions of nanoparticles in a base fluid, as a heat transfer fluid for active BTM. Van Gils, Danilov, Notten, Speetjens, and Nijmeijer (2014) experimentally tested the performance of the low boiling point liquid Novec7000, as the medium to be used for the BTM. They found that boiling heat-transfer has several significant advantages as it allows for higher heat fluxes, better thermal homogenization of the battery and improved response, as compared to conventional methods. Jin, Lee, Kong, Fan, and Chou (2014) designed a liquid cold plate containing oblique fins with optimized angle and width. Experimental results show that the heat transfer coefficients are higher for the oblique mini-channel than for the conventional straight mini-channel cold plate. The oblique mini-channel cold plate, when the fluid flow rate is 0.9 l/min, is able to maintain the average temperature of the battery surface below 50 °C for a heat load of 1240 W. An, Jia, Li, and Ding (2017) proposed a new type of BTMS based on boiling flow in a mini-channel; it used dielectric hydrofluoroether with boiling point of 34 °C. Their experimental results show that the BTMS with boiling flow in the mini-channels can maintain the temperature of the battery around 40 °C and reduce the maximum surface temperature difference of battery monomer to about 4 °C.

Liquid cooling based BTM needs a cold source, which, for EV, is typically their air conditioning (AC) system. Cooling of the battery takes part of the cooling capacity of the AC system, which can affect the operation of the AC system. Therefore, cabin air conditioning, electronics and battery thermal management require an integrated and interactive system to control their demands; this system is commonly known as vehicle thermal management (VTM) (Zhang et al., 2015). In 2011, General Motor released the extended range electric vehicle (EREV) "Chevrolet Volt", which has liquid cooling/heating systems for the battery pack and power electronics (Zhang et al., 2015). Zhang et al. (2015) in Jilin University explored electric vehicle thermal management technologies and developed integrated VTM systems based on liquid circulation, which include HVAC, BTM, electronic devices cooling system (motor, PCU, DC-DC) and PCM thermal energy storage. Their VTM system can recover waste heat from the electric devices to support cold start and to promote HP efficiency in cold weather conditions, while cooling the battery and electronic devices using a radiator in mild weather or a chiller in extreme weather conditions. Zou et al. (2016) presented an integrated thermal management system combining a heat pipe battery cooling/preheating system with the heat pump air conditioning system aiming the comprehensive energy utilization for EV. The investigation results show that as the system is designed to meet the basic cabin cooling demand, the additional parallel branch of battery chiller is a good way to solve the battery group-cooling problem, which can supply about 20% additional cooling capacity without input power increase.

The liquids used in AC-BTM systems are typically water and a glycol solution, which, when required, are cooled by the AC system. In this work, we investigate a refrigerant-based BTM, which uses the refrigerant of the AC system; the refrigerant flows through the battery pack and exchange heat directly without using a secondary coolant. This method can eliminate the heat exchanger between the refrigerant and coolant and avoid the consequent exergy loss related to the heat exchange process. In addition, refrigerant usually has low electrical conductivity as compared to water-based coolant, avoiding in this way the occurrence of battery short circuit with an eventual coolant leak. Even in the event of an EV crash, if the battery is severely damage, the refrigerant leakage can avoid or at least delay the battery combustion. Moreover, if CO_2 is adopted as the refrigerant, it has the potential of extinguishing an eventual fire and, consequently, improves the safety of EV.

Experimental setup

Battery pack cooling module

The present work was conducted for BAK 18650 cylindrical lithium-ion batteries. Single battery parameters are listed in Table 1. The

Table 1
Single battery parameters.

Parameter name	Value
Operating voltage:	3.0–4.2 V
Type:	NCA18650
Rated capacity:	2.2 Ah
Rated voltage:	3.6 V
Battery diameter:	18.2 mm
Battery height:	65 mm