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# Review Paper on Thermal Management of Li-Ion Batteries in Electric Vehicle by Active Liquid Cooling

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***Abstract*—Due to the high reliability and cost-effectiveness, Lithium-ion (Li-ion) batteries find their wide-spread use in electric vehicle applications. However, EV batteries operate in harsh environments and the body temperature of each cell in a battery pack tends to be largely different, significantly reducing life expectancy of the batteries. Improper operating temperature will degrade the performances of electronic components, Li-ion batteries which calls for a good thermal management system. In this paper, specific attention is paid to the thermal management systems based on the active temperature control method to equalize the temperature distribution of the batteries. The battery thermal management system (BTMS) plays a vital role in the control of the battery thermal behaviour. The BTMS technologies are: air cooling system, liquid cooling system. The final aim of this work is to propose an active temperature control method to equalize the temperature distribution of the batteries.**

***Index Terms*—active cooling, thermal management, liquid cooling system, EV**

## I. INTRODUCTION

There are nowadays different blending levels of hybrid electric vehicle and pure electric vehicle available on the current automobile market. According to the blending level, various size, type and number of battery cells are mounted in EVs. Unlike conventional fuel, battery cells as an energy source have stricter requirement on working environment. They are especially sensitive to temperature. To ensure a proper thermal working environment, a Battery Thermal Management System (BTMS) will normally be integrated with battery cells [10]. Thus, knowledge about the proper working requirements of battery is vital, and what kind of management systems can sufficiently and efficiently meet these requirements.Li-ion cells suffer from high cost, no uniformity, narrow operational ranges and reliability issues, limiting their widespread application in automotive applications [1]-[3]. Moreover, when these batteries fail, serious consequence such as fires or explosions could occur, posing a threat to the vehicle operation and human life.

Therefore, the battery temperature must be crucially controlled to avoid any thermal runaway and improve the reliability and durability of battery. Particularly, the predominantly used electrical-chemistries battery such as lithium manganese oxide (LiMn2O4) battery and lithium iron phosphate (LiFePO4) battery should operate within a narrow temperature range for optimization and safety purposes [5]. The Table-1 lists the cooling method used for batteries thermal management of recent EV/HEV. It's clear that the active liquid cooling method has a good potential for the future EV/HEVs, so research on liquid cooling method is necessary.

TABLE I
LI-ION BATTERIES USED IN EXISTING EVS/PHEVS

| EV/HEV model year | Capacity(kW)/ max power (kW) | Cell number/ shape | Cooling method |
|---|---|---|---|
| Nissan leaf (2013) | 24/80 | 192/prismatic | Passive air |
| Chevy volt (2013) | 16.5/136 | 288/prismatic | Active liquid |
| Ford focus (2012) | 23/92 | 190/prismatic | Active liquid |
| Tesla model S | 85/310 | 7000+/cylindrical | Active liquid |

## II. TEMPERATURE CONTROL

The Fig. 1 shows the systematic scheme of an active liquid system. There are two loops. The upper is called the primary loop and the lower the secondary loop. The primary loop is similar to the loop in a passive liquid system, where the heat transfer fluid is circulated by pump. The secondary loop is actually an air conditioning loop (A/C loop).The upper heat exchanger instead of being a radiator works as an evaporator (EVAP) for cooling operation and connects both loops. During heating operation, the 4 way valve will be switched, and the upper heat exchanger works as a condenser (COND) and the lower heat exchanger. When a large energy capacity and power output are needed in automotive applications, battery cells are generally packed together and connected in parallel and in series to meet the specifications [9]. Some existing EVs/HEVs and the batteries employed are listed in Table 1 for information. Both air cooling and liquid cooling can be found in the industry with majority transitioning to liquid cooling methods. In terms of form factor, the battery cells can mainly be categorized as cylindrical and prismatic cells. Dimensional flexibility and their cooling techniques are thus the focus of this paper. Typical prismatic cell liquid cooling system employs thin aluminium cooling plates sandwiched between two cells. Multiple cells and cooling plates are then stacked together to form a pack as shown in Fig. 3. In an EV configuration, liquid coolant first flows into a header and is then distributed into parallel channels [6]. The flow rates distribution through the parallel channels are often not uniform due to their physical placement asymmetries. This can cause uneven temperature distribution which will consequently lead to unbalanced operation of battery cells in the battery pack with compromised capacity and performance. In addition, large internal current loops can form within the pack, which can drastically shorten the battery life.

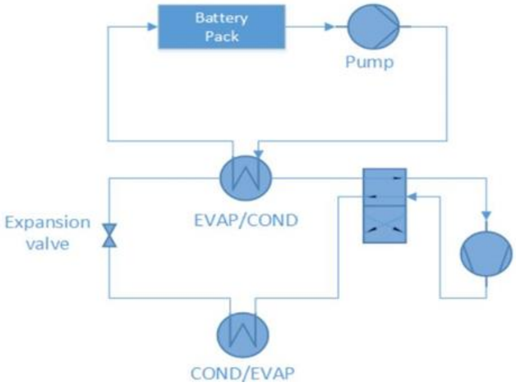

Fig. 1. Active liquid cooling system [4]

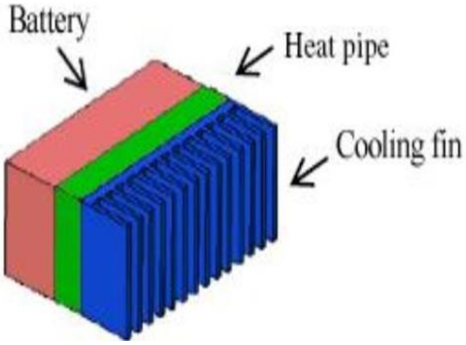

Fig. 2. Battery module [4]

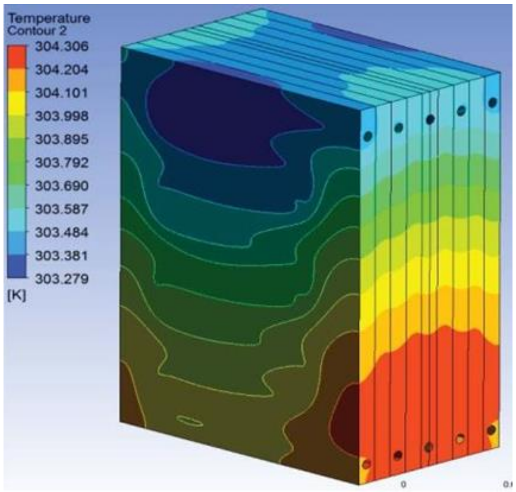

Fig. 3. Configuration of battery pack [1]

## III. CFD Results for Initial and Optimum Design

The Fig. 4 shows the three-dimensional (3-D) geometry and the computational model of the battery pack. The battery pack has 8 battery cells stacked together with cooling channels between the cells. In the initial design, cooling water is arranged to flow in the 5mm-width channel between two adjacent battery cells and there is a uniform distance of 5mm between each battery cell. There are two nozzles, comprised of the inlet with a constant flow rate of 0.065Kg/s, and the outlet with zero pressure. The battery cell is assumed to have a uniform heat dissipation of 6W per cell. The inlet turbulence intensity is assumed to be 5% and smooth wall conditions have been implemented over the inside walls.

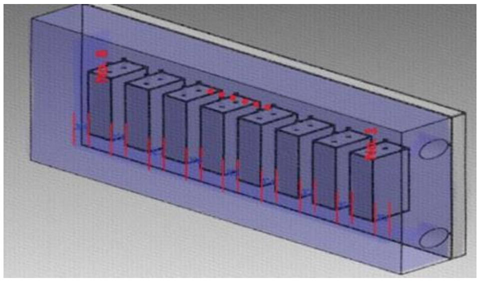

Fig. 4. Battery design [4]

The temperature, velocity distribution at the middle plane are shown in Fig. 5(a), (b) respectively at initial condition. It can be seen that the further the coolant channels are away from the inlets/outlets, the higher the static coolant pressure is. Similarly, the flow rate of the coolant channels between two battery cells decreases with the accumulated pressure. Therefore, the temperature of battery cell increases gradually for a given heat loss within each cell and this leads to the inhomogeneous temperature distribution over the battery pack, which is a common and hazardous problem for the thermal management of the battery pack. The average temperature of each battery cell is tabulated in Table 2. The minimum temperature ($26.62^0$c) exists in the first battery. The temperature of the sequentially placed battery cells increases monotonously with the minimum ($26.62^0$c) and maximum ($33.5^0$c) temperature observed in the first and last battery cells, respectively. The average temperature of the battery pack is $29^0$c and their standard deviation is $2.49^0$c.

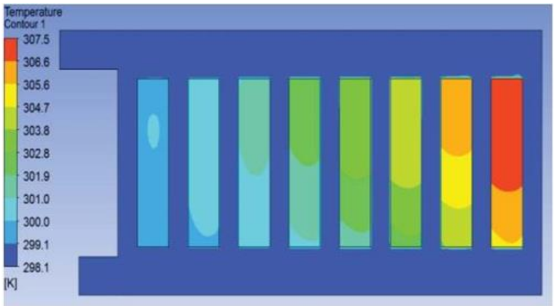

Fig. 5 (a). Temperature distribution

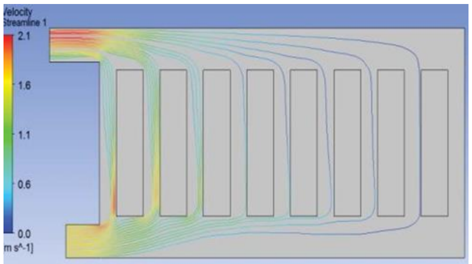

Fig. 5 (b). Velocity distribution

TABLE II
AVERAGE TEMPERATURE IN DIFFERENT BATTERY CELL [4]

| Battery cell | Temperature (°C) | |
|---|---|---|
| | initial | optimized |
| 1 | 26.62 | 27.22 |
| 2 | 27.03 | 27.03 |
| 3 | 27.65 | 27.12 |
| 4 | 28.52 | 27.07 |
| 5 | 29.63 | 26.98 |
| 6 | 30.72 | 27.29 |
| 7 | 32.05 | 27.35 |
| 8 | 33.57 | 27.48 |

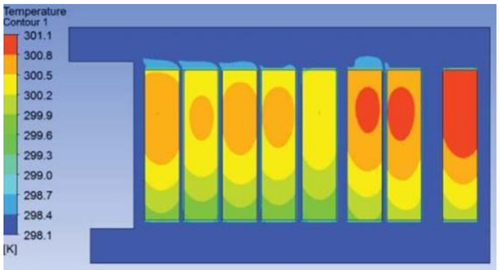

Fig. 6 (a). Temperature distribution at optimum condition

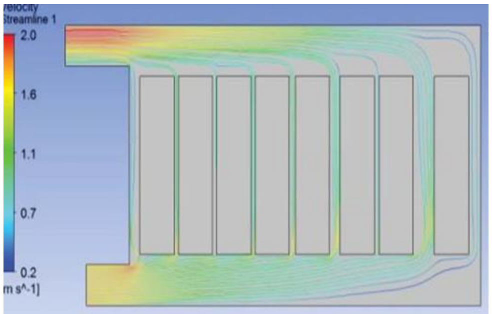

Fig. 6 (b). Velocity distribution at optimum condition

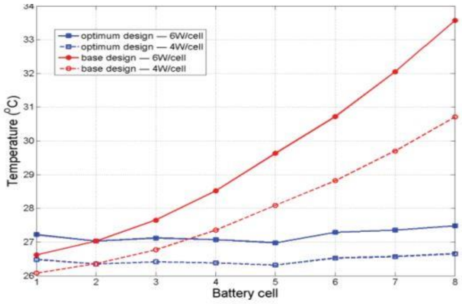

Fig. 7. Comparison of initial and optimum design

## IV. EXPERIMENT

The typical lithium-ion battery's desirable operating temperature is 25～45℃. As it is close to the room temperature, the traditional air-cooled or indirect water cooling is difficult to control at the optimum temperature continuously and effectively. To solve these difficulties, herokazu hirano developed "Boiling Liquid Battery Cooling" for higher heat transfer and improved the safety from thermal runaway [7].The ten lithium–ion cells are connected in series. Lithium ion ells are laminate type, 3.7V nominal voltage and 1Ah capacity. The tabs are bonded by ultrasonic welding. All cells' temperature, center cell's temperature distribution, a tab, the liquid and the vapour temperature are also measured. Between cells, a spacer is located to make the coolant liquid and vapored gas flow smoothly. Several types of spacers are experimented, including porous material, microfiber cloth and plastic. Spacers work not only as the path of coolant liquid, but also they work as tips for stable boiling. As the battery is directly immersed into the liquid, high electric resistance is required. Boiling temperature is selected based on the battery operating temperature. Also the liquid coolant is stable at high temperature, non-flammable and environmentally friendly. In this study the hydrofluoroether and perfluoroketone were tested [8]. The configuration of cooling system is shown at Fig.8. The coolant liquid is heated and vapored gas is cooled down and condensed by the external heat exchanger.

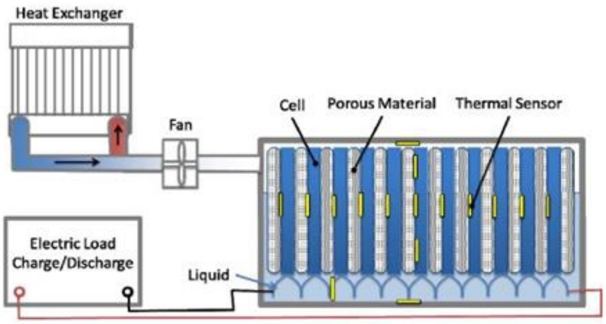

Fig. 8. Cooling system construction

Charging and discharging cycles are 5 times. Charging is done by the constant current charge followed by the constant voltage charge. Discharging is done by the constant current. Experiments are carried out by 10C and 20C charging /discharging rates; the time for full discharging is 6 minutes and 3 minutes respectively. The following graph shows charging and discharging.

Fig. 9(a) and Fig. 9(b) shows one of the comparisons between natural air-cooling and our "Boiling Liquid Battery Cooling" system. The amount of coolant liquid for this experiment is set to soak all cells completely Moreover the natural air cooling causes the temperature difference of around 10℃ among cells, and the difference does not decrease after charging and discharging cycles.

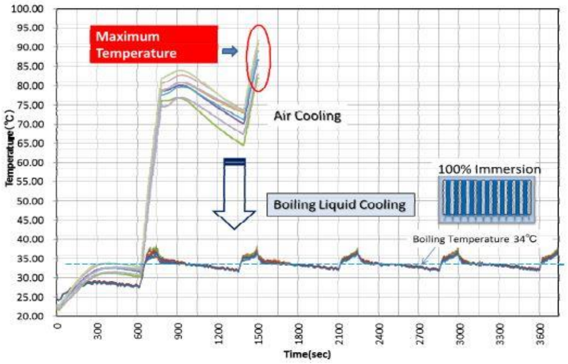

Fig. 9(a). Liquid boiling cooling vs. air cooling at charging/discharging rate 10C

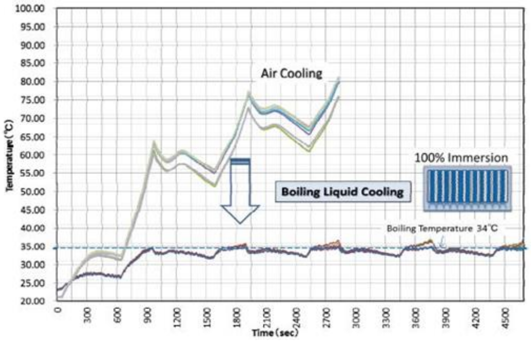

Fig. 9(b). Liquid boiling cooling vs. air cooling at charging/discharging rate 20C

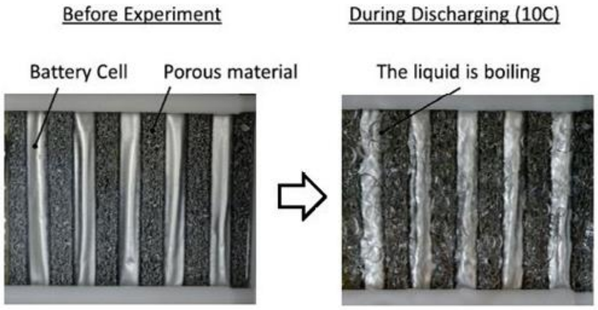

Fig. 10. Boiling status: steady boiling occurs during discharging

## V. CONCLUSION

This paper has proposed an optimization method for distributing battery cells in equivalent individual cell temperature by controlling the coolant flow rate. The results show that all cells within the battery pack can be maintained within a few °C of each other during operation. Therefore, unbalanced electrical properties can be alleviated between different cells so that the overall performance and maintenance of the battery pack is improved. Currently battery thermal management is a crucial issue. The steady temperature control is very important to secure the safety more. This fundamental research makes it clear that the “Boiling Liquid Battery Cooling” is a strong measures for lithium-ion battery thermal management. “Boiling Liquid Battery systems can control the battery’s temperature at optimum temperature under any conditions. Also the result shows that the high capillary pressure material makes the heat transfer very effectively with minimum coolant liquid.

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