COMPARISON BETWEEN DIFFERENT BATTERY THERMAL MANAGEMENT SYSTEMS DURING FAST CHARGE CYCLES

Marco Bernagozzi[1*], Anastasios Georgoulas[1], Nicolas Miché[1], Cedric Rouaud[2], Marco Marengo[1]

[1]Advanced Engineering Centre, University of Brighton, Brighton, BN2 4GJ, United Kingdom
[2]Ricardo Plc, Shoreham-by-Sea, BN43 5FG, United Kingdom

ABSTRACT

Aiming to improve on fast charge timings, all-electric range and to reduce costs and complexity, a Battery Thermal Management System (BTMS) with Loop Heat Pipes (LHPs) and graphite sheets is proposed. The LHP placed at the bottom of a prismatic cell module will transfer heat from the cells to a chiller, already part of the HVAC system of the vehicle (hence reducing complexity). Graphite, due its woven structure, provides excellent heat transfer in one direction, and insulation from cell to cell. LHPs do not need pumps or moving parts, nor they need additional energy sources to transfer heat, contrarily to an active forced convection system using fans or pumps. This work investigates the performance between the passive BTMS proposed by the Authors, another passive cooling method (free convection) and an active BTMS (liquid cold plate), thanks to a previously validated code. It resulted that free convection, compared to the LHP-based and cold plate BTMS, can contain maximum cell temperature at low values of C-rates, but is not able to reduce the temperature once the vehicle returns to normal driving conditions. Furthermore, results showed potential for the LHP BTMS to contain the cell temperature below 50°C at 5C fast charge conditions (7 minutes) and to reduce the maximum cell temperature by 7.9ºC compared to free convection and even by 2ºC compared to the active liquid cold plate.

1. INTRODUCTION

The evident deteriorating of the Earth's environmental conditions during the last 40 years has pushed governments worldwide to take necessary actions to reduce emissions of GreenHouse Gases (GHG). Amongst the various strategies sought, the electrification of passengers' transportation seems one of the most promising. However, despite the steep growth in numbers of the recent years, Electric Vehicles (EVs) accounted only for 2.6% of global car sales and about 1% of global car stock in 2019 [1]. In fact, the spreading of EVs is hindered by customers having reservations on limited all-electric range, elevated cost and long recharging time [2]. Since temperature is critical for the performance and operative life of the battery pack in an EV, a proper Battery Thermal Management System (BTMS) can help address these issues. The motivation behind this work is to find a BTMS that consumes less power (to increase the range of the vehicle), that needs few parts and low maintenance (to keep the overall vehicle cost low) and finally, the design needs to be efficient in containing the temperature increase during fast charge. On top of that, a proper BTMS needs to respect the three levels of requirements: at cell level, the temperature gradient across each cell surface needs to be maintained between 3-5°C; at module level temperature homogeneity needs to be respected, hence the temperature difference between the cells of one module should not be greater than 5°C; overall, at pack level, the cell temperature for optimum performance and long operational life needs to be maintained between 25°C and 40°C. A more forgiving temperature threshold of acceptable performance is set at 50°C, also thanks to the recent improvement on battery technology. Finally, a safety threshold is set at 60°C, to steer clear of thermal runaway risks.

To respect these requirements, the Authors proposed a BTMS comprising of Loop Heat Pipe (LHP) and graphite sheets [3]. LHPs act as thermal vector from the bottom of a battery module to a chiller included in the HVAC system of the vehicle. Graphite sheets are sandwiched in between the cells, allowing for excellent heat transfer on the face of the cell, and poor heat transfer from one cell to another

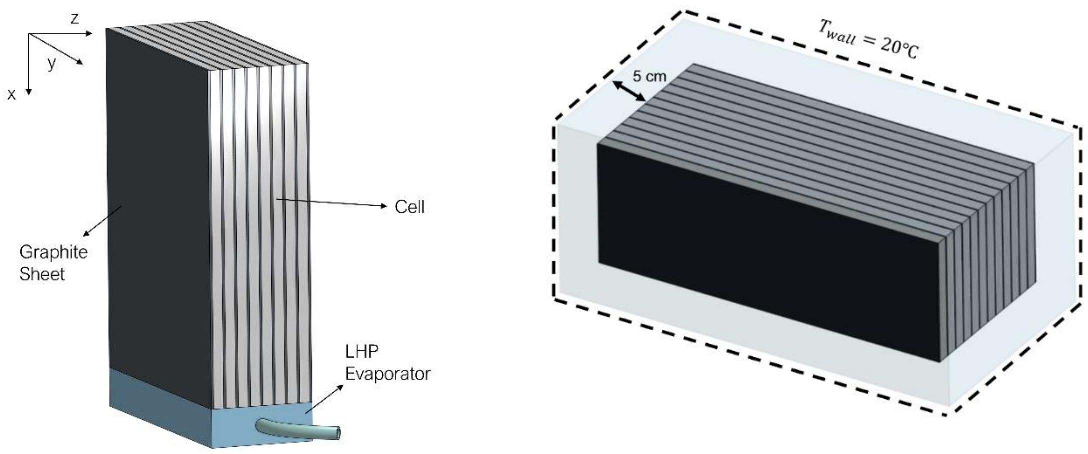
*Corresponding Author: M.Bernagozzi3@brighton.ac.uk

(delaying the spreading of temperature increase in case of a failure event). This design, depicted in Figure 1a was studied by the Authors through a Lumped Parameter Model (LPM) validated thanks to results obtained by an experimental demonstrator. For the mathematical details of the LPM and the experimental set up, the reader is kindly redirected to the Authors' previous work [3]. In the present paper, the LPM is slightly modified to account for free convection, and it used to compare the performances over different fast charge C-Rates between the same 12-prismaric cell module cooled by the LHP based BTMS, free convection and liquid cold plate, respectively.

2. COMPARISON WITH FREE CONVECTION AND LIQUID COLD PLATE

2.1.Modifications to the LPM

Free (or natural) convection happens when there is no forced velocity of the fluid, but when a body force acts on a fluid subjected to density gradients. The density gradient is due to a temperature gradient and the body force is due to the gravitational field [4]. Free convection is used in the Nissan Leaf, for many years the most sold EV worldwide. For most non-demanding application, free convection works fine, however it is the interest of this study to verify what happens at high level of fast charging and, most importantly, during the immediately following driving period. Simply, a free convection BTMS is when the module is enclosed in a volume, with a fixed air gap between it and the volume walls. The module structure of 12 prismatic cell and their dimension were maintained from [3]. To model this new BTMS, modifications were applied to the LPM utilized. Particularly, to reproduce the transient situation and the "long"-term effect (reproducing a several minutes long event), the increase in temperature of the air entrapped inside the battery module was also considered. Figure 1b displays the schematic of the control volume considered around the 12-cell module. As first conservative approximation, a 5 cm uniform gap was considered between the cells and the envelope of the module, which was assumed to be at a fixed temperature of 20°C throughout.



(a) (b)

Figure 1: Schematic of (a) the proposed BTMS design [5] and (b) of control volume used in the free convection numerical simulations.

To reduce computational demands, a single middle cell was modelled, exchanging heat to the adjacent graphite sheets from the side and with the air from front, top and bottom sides. Hence, a new equation was added to the solving ODE system:

$$m_{air}c_{p,air}\frac{dT_{air}}{dt} = \frac{T_{c,1} - T_{air}}{R_{amb,top,c}} + \frac{T_{g,1} - T_{air}}{R_{amb,top,g}} + \frac{T_{c,2} - T_{air}}{R_{amb,side,c}} + \frac{T_{g,2} - T_{air}}{R_{amb,side,g}} + \frac{T_{cw} - T_{air}}{R_{aircw}} \quad (1)$$

where m_{air} is the mass of the entrapped air, where the volume is considered (and hence the gap between module and containment wall), the suffixes c and g indicate the cell and graphite, respectively, while the suffixes 1 and 2 indicate the top and middle node, which are used for the top and side convection, respectively; T_{air} is the air temperature; $R_{amb,top,i}$ and $R_{amb,side,i}$ are the thermal resistances associated to the top and side free convection. Finally, T_{cw} is the temperature of the containment wall of the module, which is kept fixed at 20°C, and air exchanges heat with it through the thermal resistance R_{aircw}. Each one of the right-hand terms of equations (1) was added to the ODE solving the corresponding node.

Different thermal resistances are needed because three different empirical correlations were used for the Nusselt number to better describe the problem, presented in Table 1. In fact, for a vertical plate heated relative to an ambient fluid (equation (2), since the plate is aligned with the gravitational vector, the buoyancy force acts exclusively to induce fluid motion in the upward direction. However, if the plate is not aligned with gravity, the buoyancy force has a normal component, as well as parallel, to the plate surface. If the plate is horizontal, the buoyancy force is exclusively normal to the surface (equation 3), typically meaning that there will be a reduction in free convection heat transfer. Equation (4) consists in the empirical correlation to describe free convection of a vertical cavity, to represent the heat transfer from the containment wall to the cells.

Table 1. Empirical correlations used for describe the free convection around the 12cell module by means of the Nusselt (Nu) and Rayleigh (Ra) number [6].

Side of the cell – Vertical plate	$Nu_{side} = 0.68 + \frac{0.67Ra^{1/4}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{4/9}}$	(2)
Top of the cell – Horizontal Plate	$Nu_{top} = \begin{cases} 0.54Ra^{1/4} \text{ for } 10^3 < Ra < 10^7 \\ 0.15Ra^{1/3} \text{ for } 10^7 < Ra < 10^{11} \\ 1 \quad for \quad Ra < 10^3 \end{cases}$	(3)
For the containment wall – vertical cavity	$Nu_{cw} = 0.22\left(\frac{Pr}{0.2 + Pr}Ra\right)^{0.28}\left(\frac{H}{L}\right)^{-1/4}$	(4)

2.2. Comparison between the different BTMS

The other BTMS considered herein is the liquid cold plate already introduced [3], which numerical code was provided by the industrial collaborator Ricardo plc, and the LHP based BTMS already developed by the Authors. In order to provide a fair comparison on a 12 cell module, the geometry of the LHP was fixed to the one utilized in the experimental demonstrator of [3], and the number of evaporator applied to the module was varied, as shown in Figure 2.

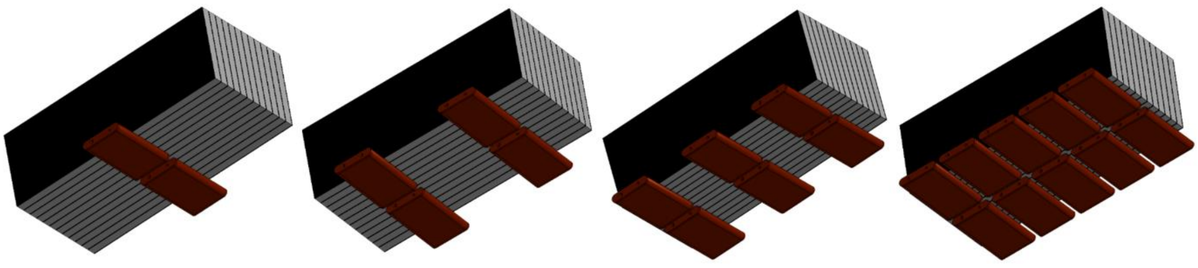


Figure 2: LHP based BTMS with varying number of 2,4,6,10 LHP evaporators.

Thus, the three BTMS (LHP, cold plate and free convection) were evaluated on 5 different driving cycles, each including a different degree of fast charge (1 to 5C as shown in Table 2) followed by 30 min of driving at 1C. The reason behind the choice of evaluating the behaviour after the charge was to investigate if and how the BTMS was able to reduce excessive temperature during operation.

Table 2. Timings associated at the different fast charge levels.

	Fast Charge Times [min]
1C	36
2C	18
3C	12
4C	9
5C	7

Figure 3 presents respectively the trends results of the three BTMS, while undergoing the different driving cycles. Looking at the free convention case, it is evident how the temperature is ever-increasing on each case studied, with only the slope changing depending on the heat generation rate magnitude. Interestingly, the temperature after the 2C fast charge, that would still reduce the charge time under 20 minutes, is below the optimum threshold of 40°C (38.3°C). However, it then keeps on increasing for the following half an hour up to 45.5°C. Similar behaviour is found in the other C-rate cases. Looking at the cold plate case instead, it is evident how, with respect to the free convection case, not only the maximum temperature at the end of fast charging is contained, but also the temperature consistently decreases in the 1C discharge section. It is worth reminding the reader that ethylene glycol runs in the liquid cold plate at 20°C from the HVAC system of the vehicle. Figure 3 shows the temperatures keep on decreasing asymptotically towards that threshold. For this comparison, the scenario with 6 LHP evaporators applied to the module was chosen. Figure 3 shows that the design allows for an excellent containment of the maximum temperature during fast charge and for a subsequent temperature reduction in the 1C driving phase. A sharp decrease can be seen right after the end of the fast charging section (identifiable by the different peaks on the temperature trends), followed by a flattening of the trends towards a quasi-steady state condition.

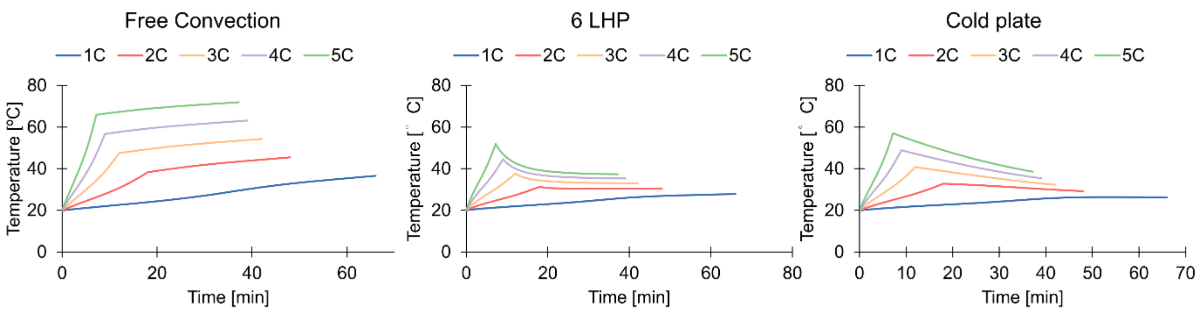


Figure 3: Comparison between the three considered BTMS over the 5 different driving cycles; charging times are 36 minutes for 1C, 18 minutes for 2C, 12 minutes for 3C, 9 minutes for 4C and 7 minutes for 5C.

Looking at the numerical results, Figure 4 and Figure 5 provide a graphical representation of the comparison between the different BTMS in terms of maximum temperature after fast charge and after driving for 30 min at 1C, respectively. Firstly, the difference between free convection and the other BTMS becomes evident from 2C and up, while at 1C free convection performs in line with the other options, even outperforming the 2LHP scenario by 2.5°C. This is mostly due to the LHPs not experiencing start-up at low powers. While free convection and liquid cold plate present a relatively uniform straight-line trend, the LHP BTMS shows a slope change between 1C and 2C, identifying that the boiling process has taken place.

The differences between the systems become even more evident when comparing the final temperatures (Figure 5) where there is an ever-widening gap between the free convection trend and the ones of the other BTMS, identifying thus the biggest distinction between the BTMS operations and fundamental difference between the investigate solutions. In fact, free convection is not able to reduce the temperature further while the vehicle resumes its journey after the charging process.

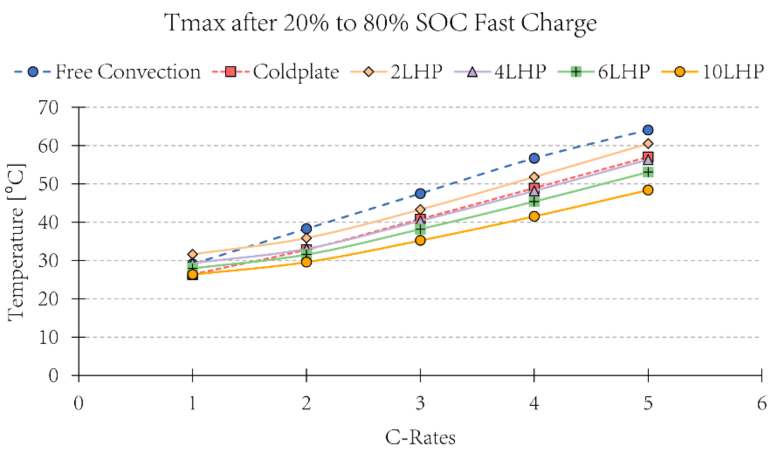


Figure 4: Comparison between maximum cell average temperatures at the end of fast charging with different C-rates, with the application of different BTMS.

Comparing instead the cold plate versus the LHP designs, both graphs show that from C-rates from 2C to 5C, the 4LHP, 6LHP and 10LHP designs perform better in terms of maximum temperature reduction during fast charge, while at 1C the cold plate is better performing, for the reasons above mentioned. Whereas, looking at the final temperatures, the comparison is a bit closer, with the cold plate giving the same temperature than the 6LHPs design at 4C, and giving lower temperatures at lower C-rates.

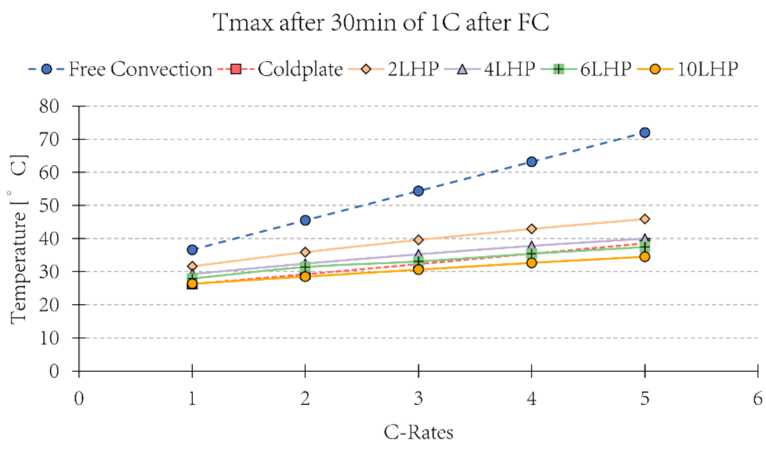


Figure 5: Comparison between final cell average temperatures at the end of the different tests, after the 30 minutes of 1C discharge, with the application of different BTMS.

3. CONCLUSIONS

In this paper, a series of investigations were performed to assess and improve the applicability of the proposed LHP-based BTMS to the automotive sector, specifically targeting the EV world and in particular a 12-cell module. A comparison between three different BTMS was conducted: free convection (passive), liquid cold plate (active) and LHP-based (passive). With a glance on a future real application, four different configurations of the LHP-based BTMS were considered, varying the number of evaporators applied to the module (2,4,6 and 10 evaporators). Numerical simulations with a validated LPM were performed over five different fast charge cycles, including fast charge from 1C to 5C, followed from a 30 minute period of driving at 1C. This final stretch was added to investigate what happened following the fast charge stop, if it provided further thermal stress the battery pack. The concluding remarks are listed below:

- The design with 10 LHP evaporators applied to the module is able to keep the cell temperature below 50°C at 5C fast charge conditions, which provide fast charge in 7 minutes; this would represent a massive improvement, however of difficult implementation considering the trade-off cost-weight.
- Lighter design comprising of 4LHP and 6LHP evaporators would still contain the maximum temperature in the acceptable range (45.4ºC and 48.2ºC, respectively) at 4C fast charge, which is still less than 10 minutes; at fast charge of 3C (12 minutes) they contain the maximum cell temperature inside the optimum range (<40°C). These would represent improvement to the current state of the art.
- Free convection, compared to the LHP-based and cold plate BTMS, can contain maximum cell temperature at low values of C-rates, but is not able to reduce the temperature once the vehicle returns to normal driving conditions.
- Using the 6 evaporator case as example, the passive LHP-based BTMS proposed in this work lowered the maximum cell temperature on average after the 5 fast charge cycles by 7.9ºC compared to free convection and by 2ºC compared to the active liquid cold plate.

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