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Transportation Research Procedia 70 (2023) 162–169

Transportation Research Procedia

www.elsevier.com/locate/procedia

8th International Electric Vehicle Conference (EVC 2023)

Novel Loop Heat Pipe System for EV Thermal Management of Batteries: Effects of Ambient Temperatures

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Abstract

Building from previous successful results from the Authors, a Loop Heat Pipe (LHP) based Battery Thermal Management System (BTMS) is investigated over a range of different ambient temperatures (from 20°C to 50°C), using a state-of-the-art environmental chamber. LHPs act as thermal vector from the bottom of the battery pack to a remote chiller, while graphite sheets allow to achieve a satisfactory level of temperature homogenization of the cells surface, with low added weight. This design was developed aiming to improve on fast charge timings, all-electric range, reduce costs and complexity, and decrease maintenance requirements. Preliminary studies showed the potential of this innovative BTMS to give better performances than standard active counterparts. The aim of this work is to extend the investigation towards a practical application, by matching experimental results obtained in the environmental chamber with a validated numerical Lumped Parameter Model and extend the results database to different geometries and material/fluid configurations, to support the adoption of this technology by automotive manufactures. Results showed a successful validation campaign, with average temperature discrepancy between the experimental results and the numerical prediction of 0.4°C. Further simulations results demonstrated how the proposed BTMS performs efficiently at higher temperatures, limiting cells maximum temperatures below 60°C even at ambient temperatures of 50°C, increasing safety.

Keywords: *electric vehicle; thermal management; batteries; loop heat pipe; ambient temperatures*

1. Introduction

The unstoppable advance of global warming has motivated organizations worldwide to seek solutions to tackle this problem. Amongst the many, one of the most cited ones is vehicle electrification, due to the sizeable improvement it

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10.1016/j.trpro.2023.11.015

can provide in terms of Green House Gases (GHG) emissions reduction, if coupled with a renewable electricity mix (Moro and Lonza, 2018). However, despite maximum efforts deployed by researchers, governments and automotive manufacturers, Electric Vehicles (EVs) still represent only the 1% of the 2021 global passenger car fleet, although with 10% increase in sales from the previous year (International Energy Agency (IEA), 2022). Partial reasons for this can be found in the reported motivations that customers have regarding not wanting to purchase an EV, these being excessive cost, range anxiety (corroborated by limited ranges) and long charging times (Noel et al., 2019). These factors can be positively influenced by an efficient, cheaper, long duration Battery Thermal Management System (BTMS), which is how the present work ultimately aims to increase EV numbers worldwide.

In fact, one of the several challenges that EVs bring along is the thermal management of the batteries. Temperature is a critical aspect for the performance and operative life of the battery pack. It has been reported that the optimum temperature range for a Li-ion battery is between 25°C and 40°C, with heavy power and capacity losses reported both at higher and lower temperatures. The maximum temperature targets are 40°C for optimum performance, 50°C for acceptable performances and 60°C is set as a safety threshold to prevent the occurrence of disruptive phenomena (e.g., thermal runaway) (Tete et al., 2021).

In a previous work, a BTMS based on Loop Heat Pipes (LHPs) and graphite sheets was developed (Bernagozzi et al., 2021a), aimed at increasing all-electric range of the vehicle and the same time reducing cost and charging time. Thanks to an experimentally validated Lumped Parameter Model (LPM), previous results showed the potential of this passive technology to outperform a standard active liquid cold plate BTMS by reducing the maximum cell temperature by 3.6°C during a 10-min 0.2-0.8 SOC fast charge cycle (up to 4C). Given the positive results, in order to further proceed in the direction of an industrial application, the LHP BTMS was tested in an environmental chamber, to investigate its response to ambient temperature ranging from -20°C to 50°C. Results showed that the proposed BTMS worked both at very high and very low temperatures, advocating for its operational flexibility. The present work starts by replicating numerically the cooling results and hence further validating the LPM. Following, utilizing this LPM, a more realistic scenario of the cooling of a 12-cell module via the LHP BTMS is simulated, investigating the minimum number of LHP needed to maintain the cells in safe temperatures starting from 20°C, 30°C, 40°C, 50°C temperatures. As reference, results from the same scenarios when the cell module is cooled by free convection are presented.

2. Proposed BTMS with Loop Heat Pipes

2.1. Loop Heat Pipes

Loop Heat Pipes (Fig. 1 for schematic) are two-phase passive heat transfer devices, member of the heat pipe family. They were first developed for space applications by Maydanik and Gerasimov in the 70s (Maydanik, 2005), due to their high thermal efficiency and independence from gravity and orientation. They work thanks to cycles of evaporation and condensation of a working fluid that, since their inner volume is evacuated prior to first use, will fill all the volume with liquid and vapour (usually liquid will fill 50% of the empty volume). Due to the staggering high values of heat transfer coefficients ensured by the boiling phenomenon happening in the evaporator, these devices are known for having very low thermal resistances (0.01 K/W). The particularity of the LHPs, from the standard heat pipes, is that the porous structure (the so-called “wick”) is present in the evaporator only, providing two handy benefits: longer length heat transportation and lower cost, compared to a standard heat pipe (where the wick is present along the entire length). For more information about the operating principles of LHP, the reader is directed to the excellent work done by Yuri Maydanik (Maydanik, 2005; Maydanik et al., 2014). The LHP used in these experiments was made of copper and used ethanol as working fluid.

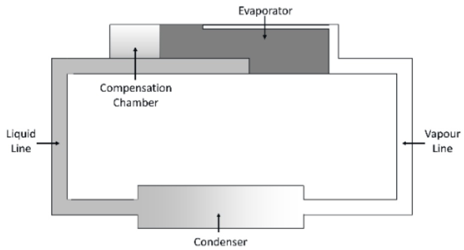
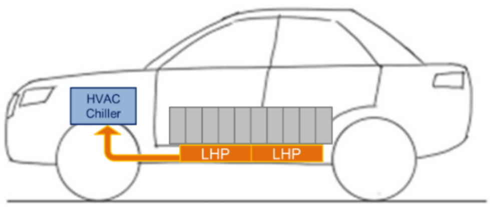


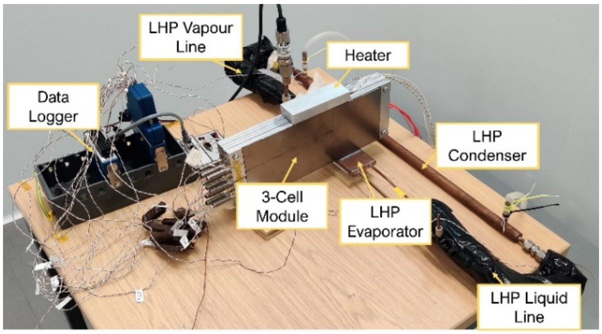
Fig. 1. Flat Loop Heat Pipe schematic (Bernagozzi et al., 2021a).

2.2. BTMS design and experimental set-up

The design proposed for the BTMS (Battery Thermal Management System) is shown in Fig. 2a. It involves an arrangement of LHPs (Loop Heat Pipes) located at the base of the battery pack modules, where the LHPs act as thermal vectors to transfer excess heat from the cells to a remote chiller. Graphite sheets are placed between the cells to ensure they maintain a uniform temperature and prevent heat from spreading between them. To evaluate the effectiveness of the cooling methods, an experimental setup was built, with dummy cells made of 5083-O aluminum plates that have the same dimensions as the actual cells. This reduces the risk of thermal stress on the actual battery cells while still allowing for testing of the cooling methods. The equipment used in the experiment shown in Fig. 2b is detailed in previous publications by the authors (Bernagozzi et al., 2021a). The experiments were conducted in a climatic chamber (TAS, 4.5x4x3.5m) with the capability of maintaining temperatures from -40°C to 60°C, and with an internal load of 4kW.



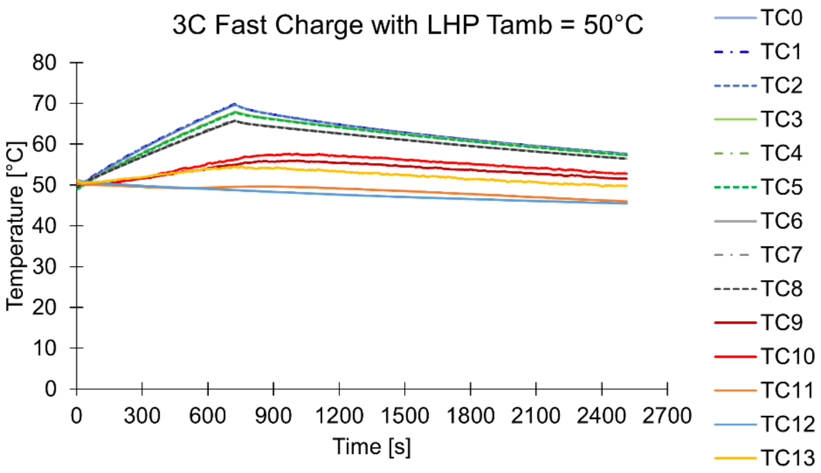
(a)



(b)

Fig. 2. Sketch of the proposed BTMS design (Bernagozzi et al., 2021a) (a) and experimental set-up used for the environmental chamber tests (b).

Experimental tests were conducted within a temperature range of 20°C to 50°C. Fig. 3 presents an example of these tests obtained with the experimental demonstrator, showing the results of the 3C cooling test at 50°C ambient temperature. The trend of the evaporator temperature line shows that the LHP is activated and properly function, also at 50°C. The 30 minutes cooldown period after the 3C fast charge section shows that the LHP passive system can reduce the temperature of the cells even at high ambient temperature. One can notice that the temperature difference from cell to cell is contained (3.9˚C) and the temperature difference top to bottom of a single cell is minimal (0.3˚C), proving the effectiveness of the graphite sheets. More experimental results are available in (Bernagozzi et al., 2023).



TC0,1,2	Cell 1
TC3,4,5	Cell 2
TC6,7,8	Cell 3
TC9	Evaporator
TC10	Vapour Line
TC11	Inlet Condenser
TC12	Ambient Temperature
TC13	Compensation Chamber

Fig. 3. Experimental results of the proposed LHP-based BTMS with ambient temperature of 50˚C, while the cells were subjected to a 3C fast charge cycle (12 minutes), followed by 30 minutes of cooldown.

3. Validation

This work will show the results obtained by replicating the cooling experiments, using a validated and benchmarked LPM developed in the open-source software Octave. The LPM is structured with a series of ODEs originating from the thermal network in Fig. 4. For more information, please refer to the previous publication by the present authors (Bernagozzi et al., 2021a).

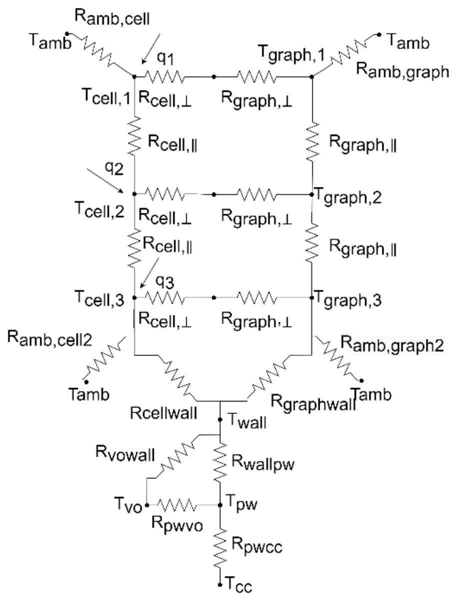


Fig. 4. Thermal Network representing the heat transfer between the cells, the graphite sheets and the LHP evaporator (Bernagozzi et al., 2021a).

As stated in the introduction, the cooling experimental tests were seeing the proposed BTMS removing heat from a 3-cell prismatic module undergoing a 3C fast charge (0.2 to 0.8 SOC in 12 minutes), while operating at ambient temperatures of 20°C, 30°C, 40°C, 50°C, respectively.

Fig. 5 shows the results of the validation procedure, where the graphs present the comparison between the average cell temperature obtained by the numerical prediction with the experimental results. The details of the numerical values are given in Table 1.

Table 1. Validation procedure results, showing the comparison between experimental data and numerical prediction at the end of the 3C fast charge cycles.

T_{amb}[°C]	T_{exp}[°C]	T_{num}[°C]	Δ[°C]
20	39.2	38.7	0.5
30	49.3	49.0	0.3
40	56.2	56.2	0.1
50	67.9	66.4	-0.6
	average		0.4

From the results depicted in Fig. 5, one can notice a close match of the experimental results with the numerical prediction, with a slight trend divergence at higher temperatures. Next steps towards improving these results could be in the direction of introducing a temperature dependent free convection coefficient in the numerical model, or to insulate the experimental battery module, as to better represent its condition inside a battery pack. Nevertheless, Table 1 shows that the temperature difference between the experimental and numerical results are minimal and averaging at 0.4°C. These results are satisfactory, providing confidence for extending the simulations to different cases and geometries, which will be the topic of the next section.

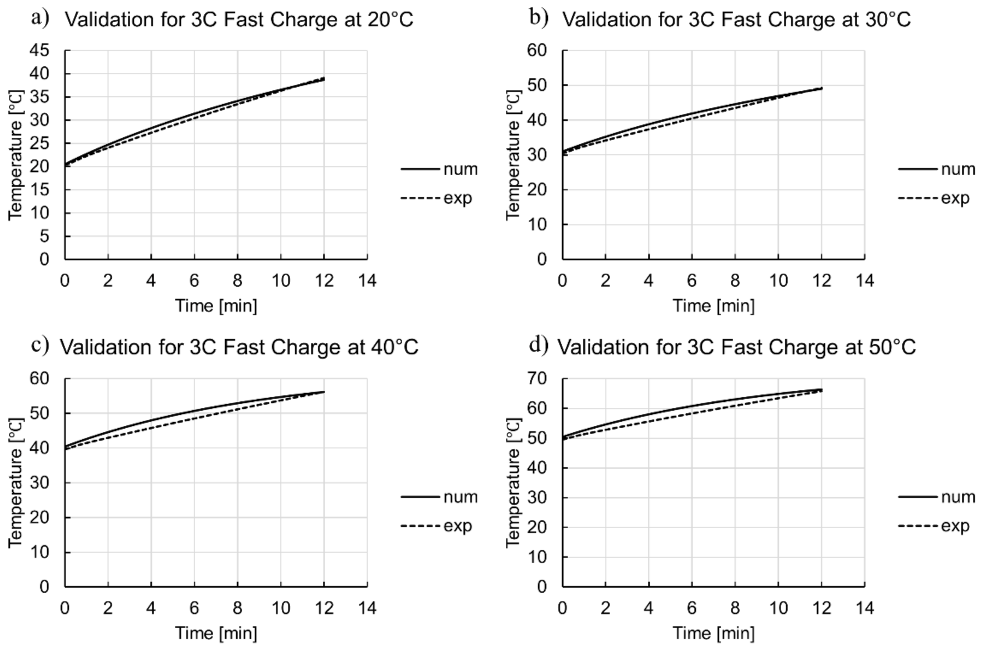


Fig. 5. Experimental validation results, at the ambient temperatures of (a) 20°C, (b) 30°C, (c) 40°C, (d) 50°C. These graphs are showing the average cell temperature over the 3C fast charge cycle, compared between simulation and experiments.

4. Numerical Results of full module analysis

Availing of the now further validated LPM, different configurations for the proposed BTMS were simulated. Namely, a battery module made by 12 prismatic cells was targeted, and the simulations investigated the effect of different cooling scenarios and ambient temperatures, with the module undergoing a 3C charge rate in 12 minutes. In more detail, Fig. 6 shows the four BTMS considered: 4 LHPs. 6 LHPs, 10 LHPs and free convection. Free convection has been chosen as it represents another passive cooling mechanism. Details of the modelling of the free convection boundary conditions are given in Table 2 (Bernagozzi et al., 2021b). To ensure the use of an efficient LHP evaporator geometry, the same evaporator used in the same experimental demonstrator has been employed in these simulations. More of the same has been added to cover the bottom surface of the battery module. In fact, 1 evaporator active zone would cover only 6% of the battery module bottom surface, and previous research by the Authors has shown that it not enough to guarantee sufficient thermal management (Bernagozzi et al., 2021b), while the considered cases are covering 25% (4LHP), 36% (6LHP), 62% (10LHP) of the module bottom surface.

Table 2. Empirical correlations used for describe the free convection around the 12cell module by means of the Nusselt (Nu) and Rayleigh (Ra) number (Incropera and DeWitt, 2007).

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

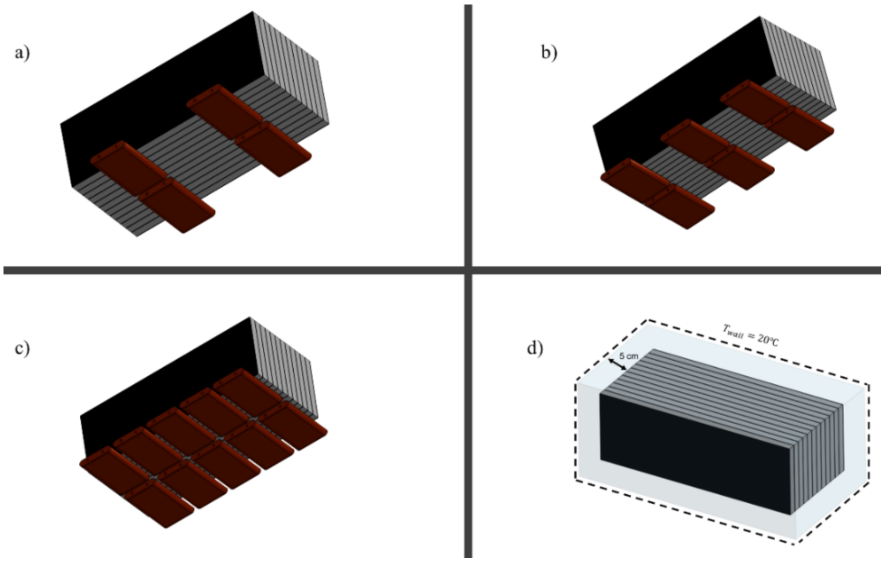


Fig. 6. Schematics of the different BTMS scenarios tested: a) 4 LHPs, b) 6 LHPs, c) 10 LHP and d) free convection.

For each simulation, the Authors assumed that the 12 cells had the same temperatures. The cells maximum temperatures when cooled down by the different BTMS are shown in Table 3 and Fig. 7.

Table 3. Simulations results of the comparison between different BTMS scenarios, at different ambient temperatures.

	Ambient Temperature			
BTMS	20°C	30°C	40°C	50°C
4LHP	37.7	44.9	52.8	62.4
6LHP	35.9	42.6	50.1	59.9
10LHP	33.5	39.6	47.3	57.3
Free convection	47.5	57.5	67.5	77.5

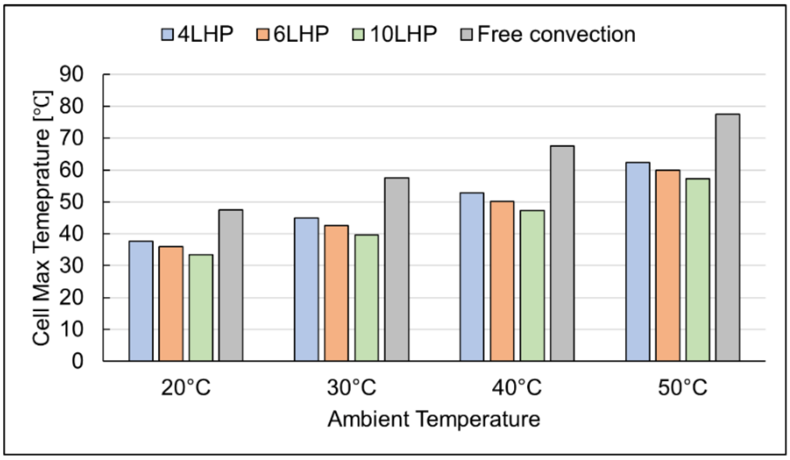


Fig. 7. Simulations results displaying how the different BTMS tested react to different ambient temperatures.

Starting to look at the 20°C results from Table 3 and Fig. 7, it is evident that the LHP-based BTMS, as already proven, works remarkably in keeping the temperature the optimum threshold of 40°C. It is worth pointing out that the cells would not get to unacceptable temperatures even under free convection (<50°C), however it was shown previously by the Authors that in this case problems arise when the vehicle resumes its journey, after charging, and the free convection is not enough to further reduce the temperature.

At 30°C, the proposed BTMS would need 10 LHPs to keep the module temperature below the optimum threshold of 40°C, reaching a maximum of 44.9°C with only 4 LHPs. Nevertheless, the temperature values with 4 and 6 LHPs are still well withing the acceptable limit. Whereas, if cells are left unattended (free convection), temperatures will reach values dangerously close to the safety limit of 60°C.

At 40°C, temperatures are already outside of the optimum limits hence why the acceptable window becomes narrower and of fundamental importance. The scenario with 10 LHP shows to notably efficient to contain the temperature increase at only 7 degrees, keeping the maximum cell temperature below the acceptable threshold, while with 6 LHP the temperature will be just on the edge of acceptability, at 50.1°C.

Results of simulations at even higher temperatures, 50°C, reveal that cells need something more thermically efficient than just air, as the temperatures of the air inside the battery module will increase to 58.8°C, and the cells up to 77.5°C. The LHP-based BTMS instead can maintain the cells temperature below the safety thresholds of 60°C, when 6 or 10 LHP are used.

5. Conclusions

Ambient temperature is a key factor in reducing performance and operative life of an EV, thus efficacious Battery Thermal Management Systems (BTMS) need to be coped adequately at different ambient temperatures. A LHP-based

BTMS was successfully proposed, tested, and evaluated by the Authors, showing very promising results. The present work aims to extend on these results, ultimately to overcome the skepticism of automotive OEM in employing two-passive devices. The objectives of this paper were to validate the one-dimensional LPM at different ambient temperatures, by replicating a set of experimental results obtained in a thermal chamber at 20°C, 30°C, 40°C and 50°C. With the validated code, the applicability of the proposed BTMS to a 12-cell module was investigated numerically, by comparing the maximum cell temperature following a 3C fast charge cycle lasting 12 minutes, when cooled by a system of 4LHPs, 6LHPs and 10LHP, respectively. Additionally, free convection results are used as benchmark comparison as passive cooling method. Following the main conclusion can be drawn:

- The validation of the LPM was successful, with average temperature discrepancy between the experimental results and the numerical prediction of 4°C, when looking at the maximum final temperature of the cell;
- At higher ambient temperature (40°C and 50°C), an EV cannot rely solely on free convection for cooling, as cell temperatures after only 12 minutes of fast charge will exceed the safety limit of 60°C;
- The LHP-based BTMS proposed by the Authors performs nicely also at high temperatures, in all scenarios tested, exception made for when using 4LHPs at 50°C, where temperature exceeded 60°C; the proposed BTMS is able to give acceptable cell maximum temperatures at 30°C, and if using 10LHP, performance is below the in the acceptable window even at 40°C ambient temperatures.

Moving forward, the next steps of the Authors research are to build an experimental demonstrator able to target a 12-cell module and continue the testing towards a practical implementation of this design in tomorrow's EVs.

Acknowledgements

The Authors would like to thank the Advanced Engineering Centre and the School of Architecture, Technology and Engineering for the economic support in attending the 8th International EV Conference.

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