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A compact and self-sustained thermal management system for electic vehicles

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Executive Summary

SELFIE is a 4 year-long European research and innovation project conducted by ten partners collaborate to develop and demonstrate a novel thermal management system (TMS) and control, implemented at a full scale electric vehicle. The TMS is comprised of a smart modular battery pack, with excellent internal thermal conductivity properties, a refrigerant cooling system and thermal storage system capable of absorbing excess heat due to fast charging, thoroughly insulated from the outside. The battery TMS is capable of keeping the battery temperature effectively within the optimal window. SELFIE aims on providing high efficiency and performance both on the battery cells, in order to ensure system longevity and cost-reductions, without compromising the passenger comfort during cabin cooling/heating operations at extreme ambient conditions. The SELFIE project will significantly increase user acceptance of Electric Vehicles by enabling fast-charging, offering significant cost reductions and elimination of range anxiety compared to other propulsion technologies.

Keywords: battery model, BEV (battery electric vehicle), fast charge, energy storage, water cooling.

1 Introduction

Electric vehicles (EVs) can contribute to the defossilization of the automotive sector amd to the redcuction of global carbon emissions that it is responsible, approximately up to a third of the total. The continuing advancements of the Lithium-ion battery cells (Li-ion) are shown as a significant energy storage and power source for the EVs. Li-ion cells are now employed to numerous vehicle designs for various performance metrics, such as full electric cars, plug-in hybrid and hybrid to be among some. Li-ion cells have increased their performance capabilities in terms of volumetric and gravimetric values due to constant R&D in a multi-disciplinary area, that combines material science, electro-chemistry, thermodynamics and heat transfer phenomena, together with software and hardware engineering. Nowadays, Gen3 and Gen4 battery cells can be utilized for high energy and high power applications. Nonetheless, Li-ion cells need to operate within a certain temperature window to ensure a safe and reliable operation [1]. Cycling or storing a battery cell outside the recommended safe-operation-area (SOA) it can result to reduced performance and potential hazardous conditions, by triggering certain degradation modes or material destabilization and thus effect the mileage capabilities, the charging performance (especially under certain climate and loading conditions) and ultimately the total life-cycle cost of application, rendering also the EVs becoming challenging to be accepted by the end-user. Up-to-date there is still plenty of space for improving the safety and performance capabilities of EVs, while various solutions for the optimal preservation of batteries within SOA being conducted, with respect to both the battery management systems (BMS) that is related to the state control of the cells by monitoring, communicating, and contolling, and also the thermal management system (TMS) in the battery multi-cell topologies, that is responsible for dissipating the heat from the generating reversible and irreversible cell losses to the outer surfaces and the cooling mediums of the design. TMS can be also used for heating the cells in certain applications, where subzero temperatures, outside the recommended SOA are applied on the cells, and can trigger fast-degrading modes or unsafety such as the plating and corresponding dendrides [2].

SELFIE project (SELFIE 2018 [3]) stands for “SELF-sustained and Smart Battery Thermal Management SolutIon for Battery Electric Vehicles” and investigates the development of a modular battery thermal management with the capability of handling with safety fast charging up to 140 kW while absorbing the heat generation excess during the fast charging conditions. One of the major objectives of SELFIE project focuses on the development of fast charging capability maintaining the thermal performance and it is to develop the most efficient and economical layout of the electric cars cooling architecture.

The modern design and optimization of the battery TMS are aimed at decreasing the charging time to 10min and maintain the potential capability of the vehicle to cruise up to 700km with several pit-stops for recharging without exceeding a total recharging time of 90 minutes. In SELFIE, a smart, compact and efficient battery system and thermal management are developed and manufactured whereby cost efficiency is taken under consideration. In this regard, a polymer composite material is used for the housing instead of the traditional and heavy metallic casing. In addition, a cooling plate and a phase change material (PCM) heat buffer are utilized in the system to keep the cells of the battery pack at an optimal temperature range and within SOA. This cooling plate is designed and optimized in order to replace the traditional cooling plate usually placed below the cells. During the course of the project, numerical models are developed and validated with results of experimental studies at battery module level, that support the R&D activities.

A significant increase of user acceptance of electric vehicles can be achieved only with further and significant cost reductions and elimination of range anxiety compared to other propulsion technologies. SELFIE makes its biggest impact here, ensuring that electric vehicles, in the not so distant future, are able to accept high charge rates without reduction of the battery lifespan and to store electric energy efficiently in their batteries with minimal losses.

2 State-of-Art thermal management systems

Battery TMS is typically engineered with direct or indirect contact of the fluid on the cell’s surface and on passive or active management depending the power consumption rates. There are plenty scientific contributions on the various cooling/heating designs [4,5] where the most prominent for the fast dissipation rates required for EVs are found to be the liquid-based solutions, due to better heat transfer coeeficent which can allow compact designs with improved volumetric densities. Hybrid approaches are being researched by combining passive materials such as PCMs together with active cooling control, either air or liquid. PCM-based TMS have raised the attention in last years due to their unique benefits in the zero consumption requirement, no moving parts, and the outstanding capabilities on thermal control [6]. PCM-based TMS is utilizing the latent heat at the phase change transition process, where in the SELFIE project the solid-liquid transition is assessed on the improvements of the TMS control, and its contribution to the selected battery pack design. Aiming for the cost-efficiency of the SELFIE design, several TMS solutions with active, passive and hybrid topologies have beed built and tested. In [7], we presented the concept of a passive TMS with natural convection, heat pipe, and PCM. It is shown that a temperature improvement up to 40.7% compared with natural convection can be achieved, by heat pipe and PCM assisted cooling system. Also, in [8] the heat pipe air-cooling systems is evaluated for the fast dissipation rates of the LTO module. As it is seen from the experimental tests, natural and forced convection decrease the average temperature on the cell by 6.2% and 33.7%, respectively. The effect of PCM and liquid-based design has been discussed in our previous study with a comparison among the PCM TMS acting with and without the active liquid support system [9]. It is observed that by using the hybrid TMS module temperature reaches 31.2 ◦C and 31.8 ◦C at the end of the charging and discharging process respectively, which has a 24.6% and 26% temperature reduction compared to the similar test but with natural convection. In this study we further assess the overall contribution of the PCM heat buffer in the TMS, by comparing the performance of hybrid cooling to the liquid-based design alone, as an attempt to further assess the system's gravimetric efficiency, safety and robusteness.

3 A novel thermal management control scheme

The battery thermal management is improved at system level by increasing the air mass flow rate in the front-end module, allowing to increase the power dissipation during fast charging. SELFIE tackles this challenge by designing a novel front end module increasing heat dissipation by 30%.

Moreover, a cold storage device (CSD) is developed to optimize the cabin comfort during high cooling demands while fast-charging. The cooling power of the EV is increased by providing sufficient cooling both to the battery cells and the cabin. SELFIE optimizes the volume and performance of the A/C loop components with the CSD, by alternating the cooling pressure levels and thus utilizing the charging/discharging energy from the CSD to consecutively support battery and cabin cooling. The overall design of the SELFIE TMS is presented in Fig. 1.

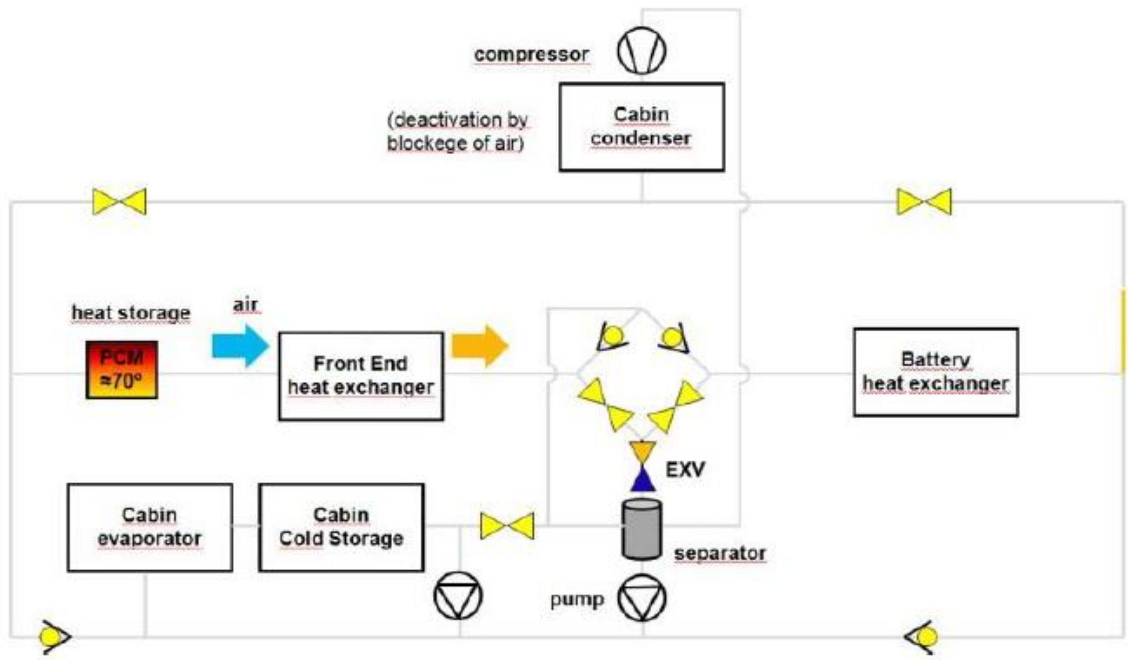


Figure 1: SELFIE novel thermal management system for the EV original draft.

4 A new hybrid cooling battery thermal management

4.1 Component development and module evaluations

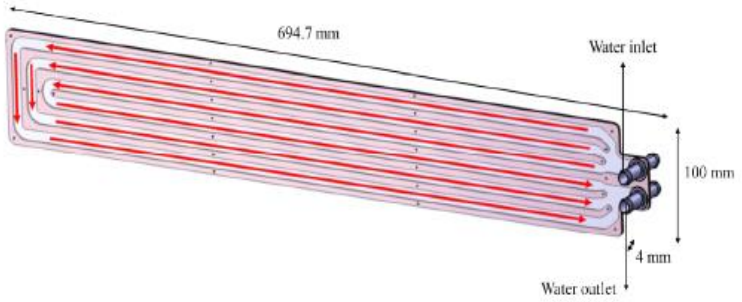
Numerical models are built in the SELFIE project to evaluate the steady-state and transient phenomena of the proposed battery pack and its interactions among the developed components. High-fidelity models are implemented to understand the most suitable fluid dynamics, such as the mass flow rates of the coolants, the inlet and back pressure of the cooling channels, to realize the best performance properties of the PCM related to the heat transferring phenomena, such as the porosity and the geometry of the internal heat buffer, and lastly to define the most prominent characteristics of the external housing. Hence, the physical characteristics of the individual components for the battery pack are well-realized and used for the design stages.

The models investigate the sub-system of the whole SELFIE pack, as attempt to reduce the modelling complexity and computational request. Also, the sub-models are combined with the high-fidelity model of the battery cells that are used for the SELFIE purposes, a high-power prismatic cell with NMC/LTO chemistry. Thirty cells are connected in series to reach the energy and power requirements of the battery module that is utilized for the development of the CFD model. To meet the current levels of the EV, three cells are connected in parallel reaching a 69Ah and then five are serialized with a total 11.5V and 0.76kWh. The final pack consists of 540 cells with a 414V nominal and 28.5kWh stored energy. The main properties of the cells and the module are listed in Tab. 1.

Table 1: Main properties of the prismatic battery cell and the multi-cell topology.

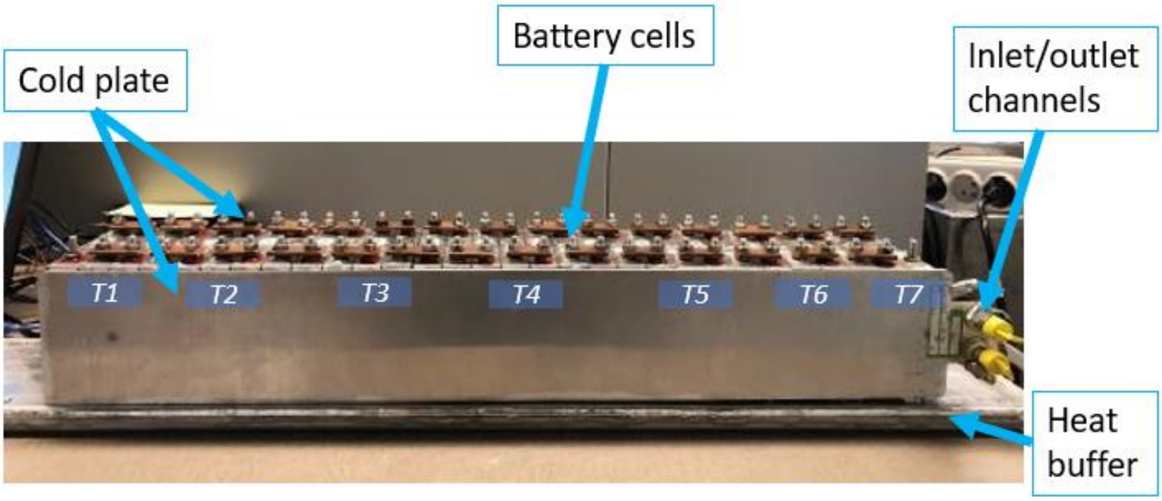
Parameter	Value	
Cell-level		
Chemistry	NMC/LTO	
Shape	Prismatic	
Nominal Voltage (V)	2.3	
Maximum voltage (V)	2.7	
Minimum voltage (V)	1.5	
Capacity (Ah)	23	
Specific Energy (J/kg)	96	
Energy Density (J/m)	202	
Weight (kg)	0.550	
Volume (L)	0.260	
Dimensions L × W × H (mm)	115 × 22 × 103	
Heat specific capacity (J/kg.K)	1150	
Thermal conductivity x,y,z (W/m.K)	31, 0.8, 31	
Module levels		
Module topology	30S1P	5S3P
Nominal voltage of the module (V)	69	11.5
Weight (kg)	16.5	8.5
Volume (L)	7.8	n.a.
Stored energy in the module (kWh)	1.6	0.76
Pack levels		
Pack topology	(5S3P) * 36S1P	
Nominal voltage of the pack (V)	414	
Sored energy in the pack (kWh)	28.5	

The performance of the SELFIE EV is optimized for various scenarios, and particularly on fast charging during normal and elevated ambient temperatures. To assess the performance at such conditions, a prototype battery module comprised of thirty prismatic battery cells is built [9]. The maximum heat rate during a fast charge is approximated based on the irreversible Joule losses and the equivalent circuit based modelling technique [10] at around 40W, where for this case study a lateral-based cold plate that attaches both left and right side of the 30S1P configuration is built. It consists of Al casing and 1 inlet/outlet U-shaped channels. Thermal interface material with c.a 3W/mK thermal conductivity is placed between the cold plate and the cells to decrease the contact resistance. On the bottom of the structure, a heat buffer plate enclosing PCM is placed, to support the fast heat dissipation rates. Fig.2 shows the developed battery module that is tested and validated during the SELFIE project.



(a)

(b)

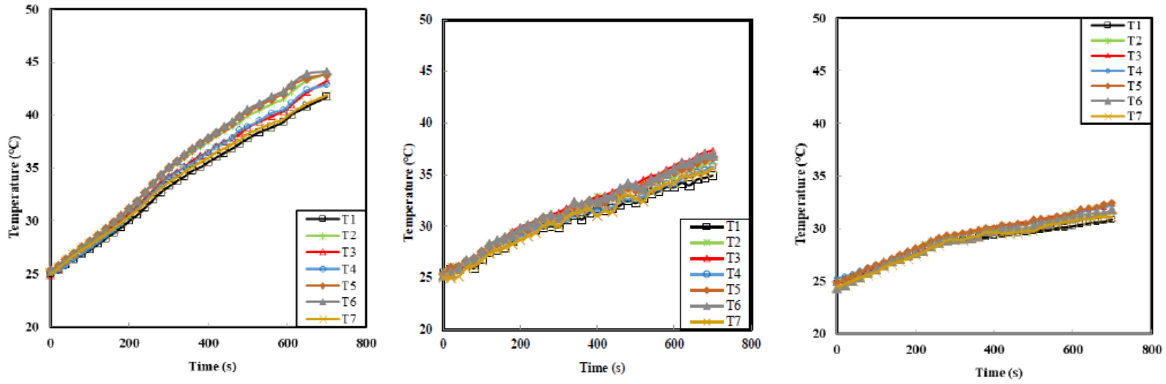


(c)

Figure 2: Components of the TMS implemented in SELFIE. (a) Cold plate attached to sides of battery cells, (b) PCM heat buffer plate placed at the bottom and (c) battery module hybrid TMS design.

Further details on the individual components can be found in previous publications [9]. Seven thermocouples k-type are placed on top of the cells and close to the current collectors as this is the hottest spot of the cells during cycling. The testing results are utilized to validate the CFD models in our previous studies, which is further used here to evaluate the performance of the module with and without the PCM heat buffer.

The experimental validations of the thermal management of a SELFIE module with PCM buffer and cold plate are presented here for three significant scenarios comprising natural convection, PCM heat buffer plate, and hybrid cooling (Fig3).



(a) (b) (c)

Figure 3: Performance comparison at a fast charge scenario. (a) Natural convection, (b) PCM heat buffer plate and (c) hybrid cooling solution.

It can be observed here that during a 5C charging scenario at the room temperature, the 30S1P battery module generates heat that is not adequently dissipated with the natural convection, as shown in Fig.3(a). Temperature in this case exceeds the SOA range and can lead to unsafe conditions and reduce performance. The temperature increases remarkably in the middle of the module, which is referred as the hottest area of the design. Fig.3(b) shows the effect with only the PCM applied. CFD results shows that the heat buffer can contribute to preserve the cells tempareerature within SOA, with an up to 15% improvement on the charging process heat control. Lastly, Fig.3(c) shows the effect of the hybrid cooling on the CFD model, where a further 24.6% improvement on the cooling performance is achieved.

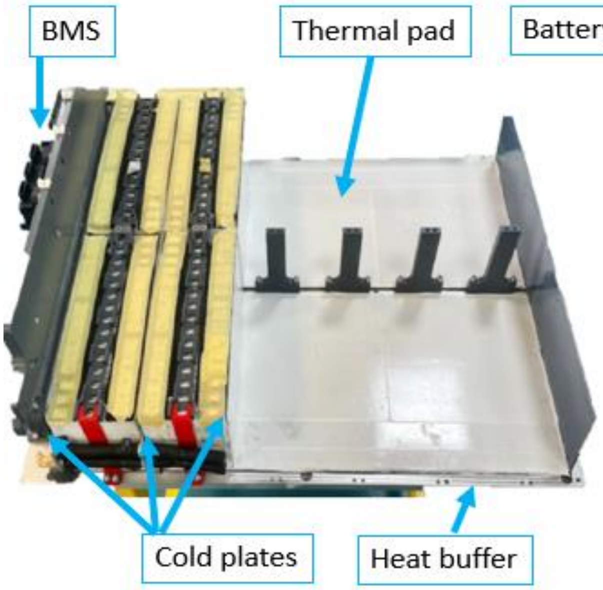
In the next section the battery pack is integrated and tested. The battery pack is comprised of 36 of 5S3P modules connected in series, that are devided into two compartments, one with 12 modules and another with 24. Each module of the battery pack integrated in the EV has 15 cells with a 5S3P topology. The characteristics of the pack are listed in Tab1.

4.2 Battery pack integration and testing

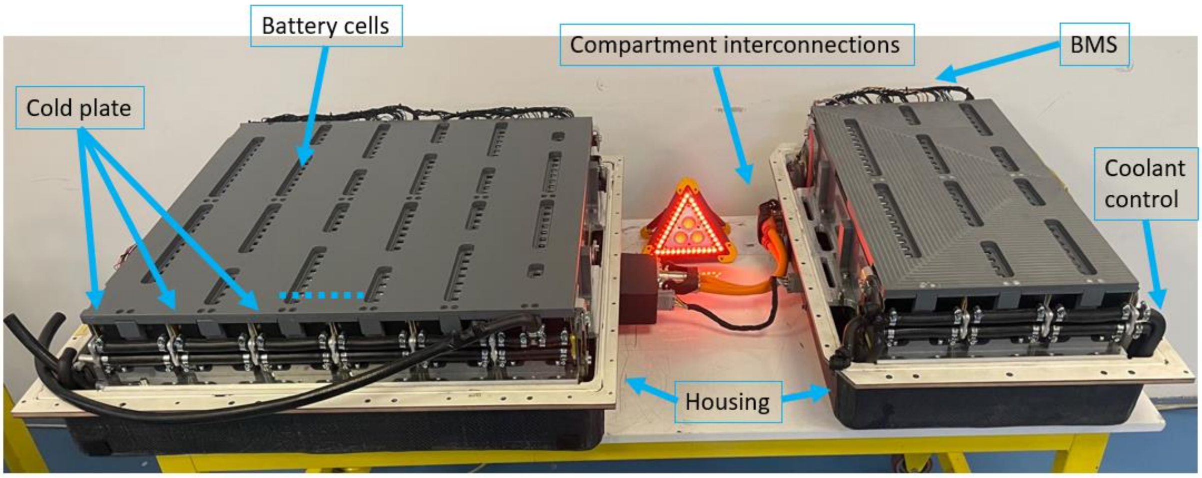
SEFLIE battery pack is placed underbody of the EV, and a two compartment configuration is used to fit the desired space. The pack design and nominal ratings are given in Tab.1. To control and monitor the safe operation of the battery cells, the open-source battery management system (BMS) foxBMS 2 is used. It is based on slave-master configuration, with one master and twelve slave boards. The BMS is capable of performance optimization and maintencane within the SOA, by voltage, temperature and current monitoring, communications and protection actions as well as passive balancing function.

The SELFIE's thermal management of high-power battery cells is comprised of an encompassing housing enclosure which provides thermal insulation and safety, the heat buffer and the cold plates which operate with liquid coolants (Fig.4a). The proposed design was defined after experimenting and analyzing various topologies and configurations of management systems, with various passive and active elements such as heat pipes, PCMs, water/glycol and air mediums. All the approaches have been transferred to multi-physics and multi-domain high fidelity models to further evaluate their performance for most relevant scenarios.

In Fig.4a the developed battery pack is shown with the integration of the heat buffer PCM plates, the gap fillers to reduce the thermal resistance, the battery cells and the BMS together with the cold plates active thermal control system. The battery pack contains in total 22 cold plates that cover the whole lateral area of the cells, with a total mass flow of 7.5 L/min. The inlet temperature of the coolant is kept constant at 10ºC. As an attempt to assess performance and safety over time the thermal behavior of the battery pack has been assessed for a configuration without PCM buffering (Fig. 4b). To be on the safe, the maximum C-rate was set to 4C instead of the 5C applied in the pre-experiments shown in Fig. 3.



(a)

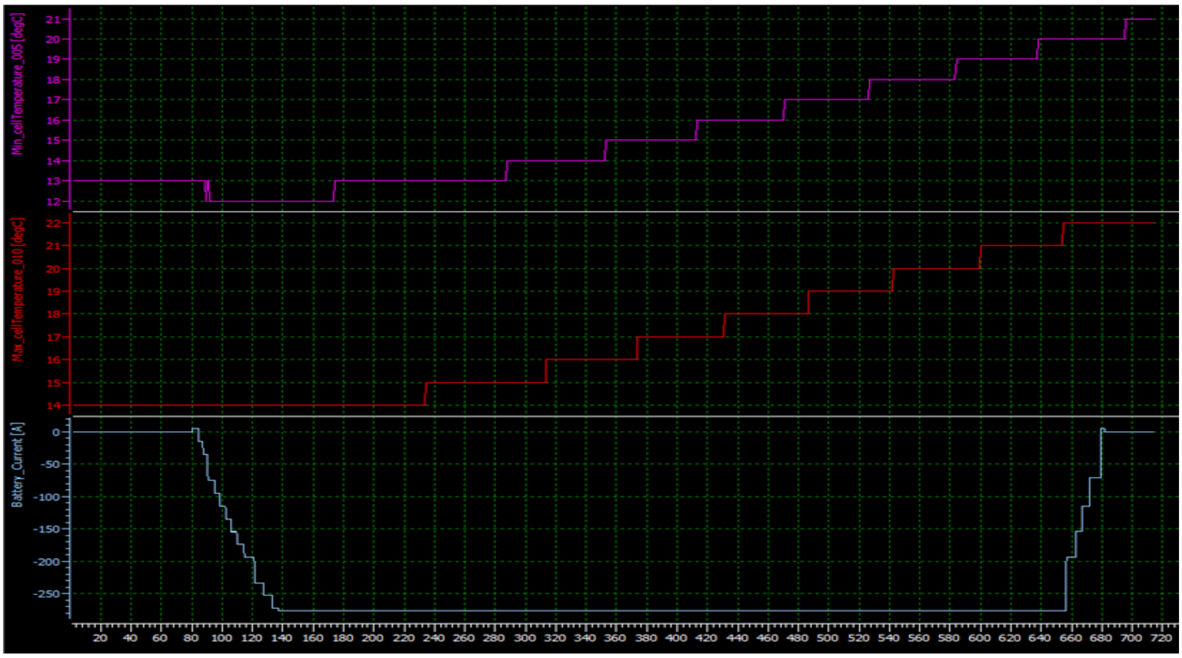


(b)

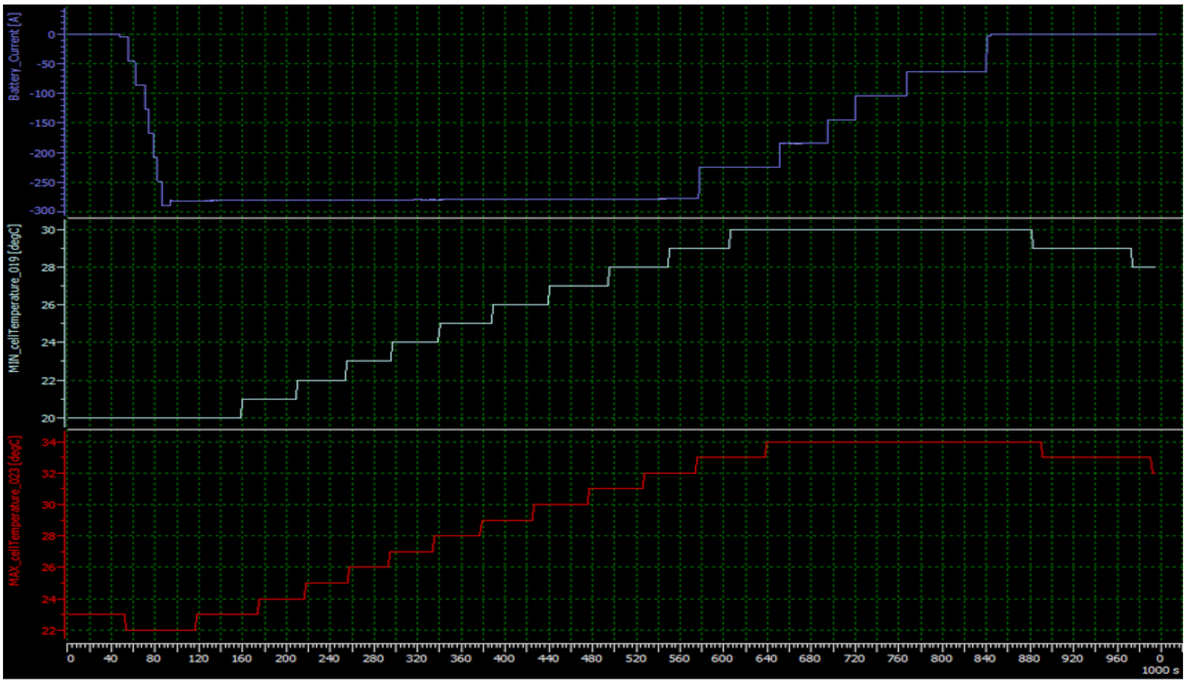
Figure 4: Different design solutions investigated in SELFIE. (a) with a heat buffer PCM-passive cooling, (b) without the PCM heat buffer.

The tests were conducted on the SELFIE small compartment being charged and discharged at 3C and 4C current rates with and without the PCM heat buffer while the liquid cooling was operated. During the tests ambient temperature measured as 19°C and the active cooling system coolant temperature set as 10°C with 7.5 L/min flow rate. Thermocouples are placed on all the cells to record their performance.

Fig.5(a) shows the measurements on the maximum and minimum cell temperature with a 4C rate (276Amps). The PCM-liquid cooling hybrid TMS is shown here. Fig.5(b) illustrates the same measurements but with only the liquid system in operations, and the PCM heat buffer removed. Both tests are performed for a 20-80% SoC window.



(a)

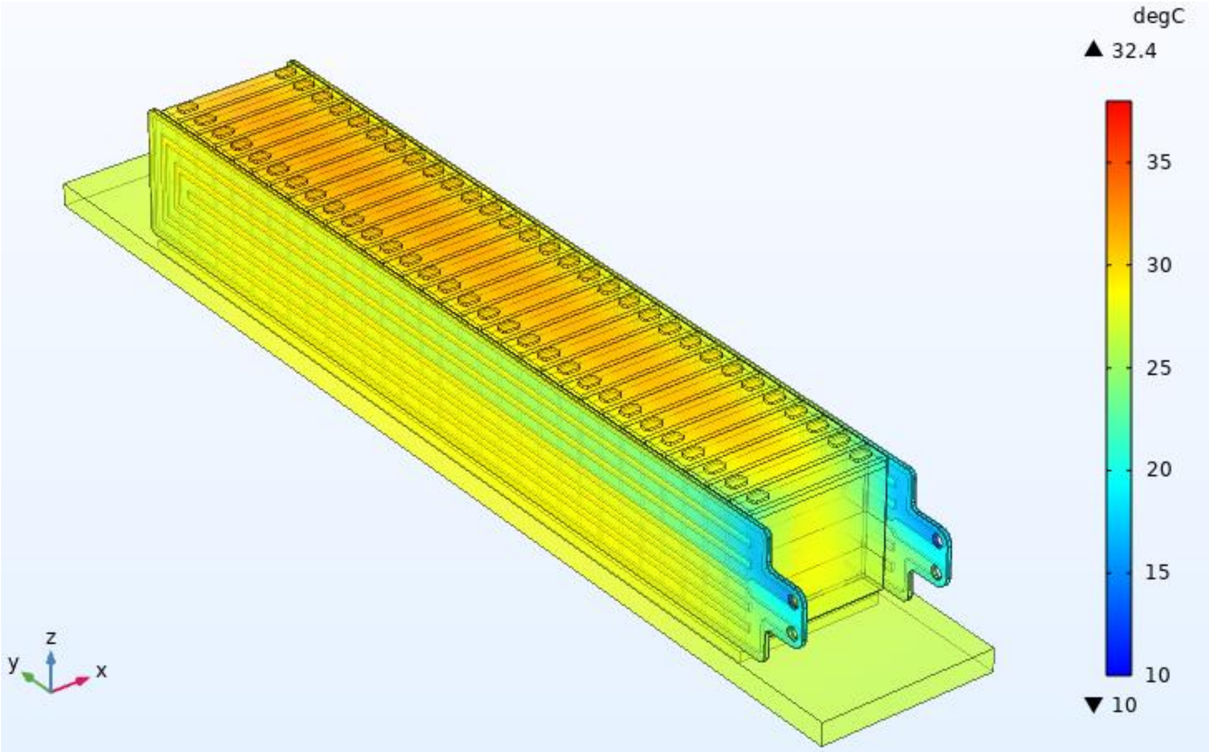


(b)

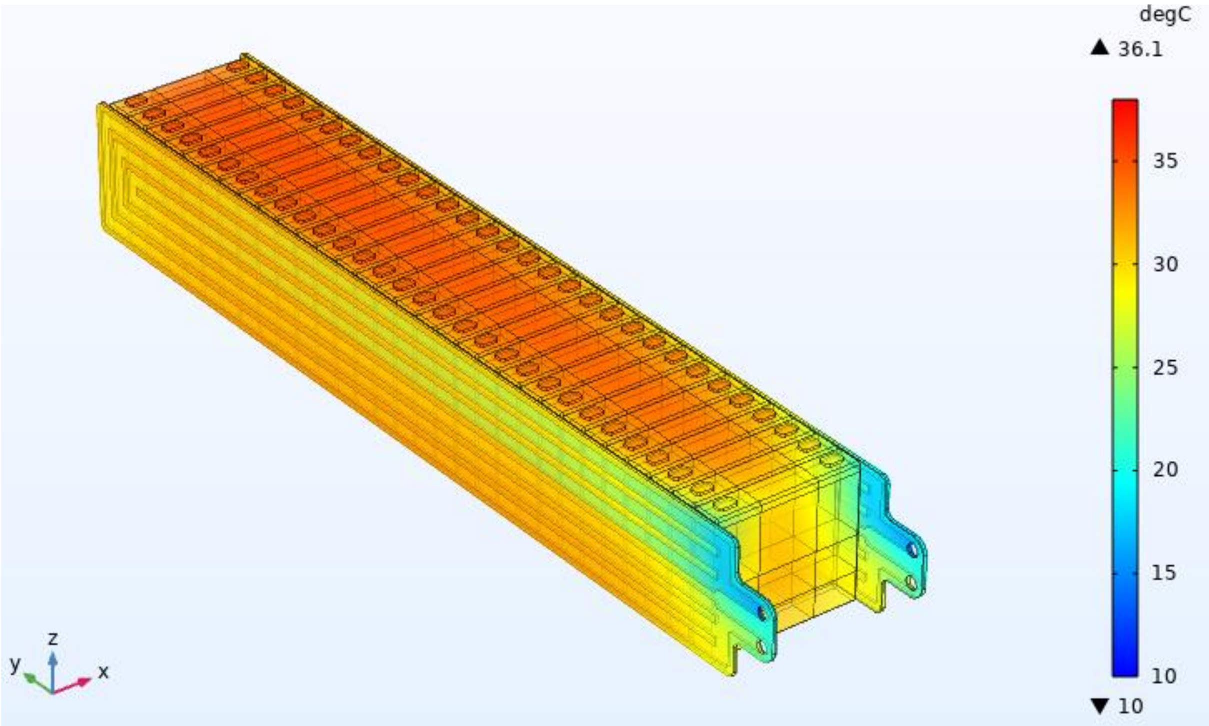
Figure 5: Cooling perfroamnce on the battery pack small compartment min and max cell temperatures for a 4C rate (a) with a heat buffer PCM-passive cooling and the thermal loop, (b) standalone liquid coolant.

It can be observed that with the hybrid TMS a max cell DT of 8°C is reached, with the final max temperature being 22°C. For the latter case with only the liquid control, up to 12°C DT is reached for the hottest cell of the module. Hence 3-4°C higher temperatures can occur without the heat buffer.

To further evaluate the the performance of both solutions, CFD modelling is conducted on the 30S1P module. Results are presented in Fig.6(a) for the hybrid TMS and in (b) for the liquid-based. A room temperature of 25 °C is applied in the model with the same flow rates for the module study.



(a)



(b)

Figure 6: Numerical evaluation of thermal performance at fast charge between (a) with a heat buffer PCM-passive cooling and the thermal loop, (b) standalone liquid coolant. Both cases performed for the 30S1P battery module.

In these results we observe the overall temperature evolution on the modules. To consider a close to reality system, the mass flow rate of the battery pack is divided here for the single module at a 0.3L/min (as an approximation on the lower dissipation rates for higher estimated impedance over lifetime: the design of the plates has been done in order to have for every end plate (plates cooling only 1 cell) 0.56 L/min, and for every plates placed inbetween each cell (plates cooling 2 sides of cells) the flow rate is 1.12 L/min) and the same inlet temperature (10^{o}C) of the coolant. Also, the current rate is the same 4C while the ambient temperature is 25^{o}C. The model details, such as boundary conditions and validations can be found in our previous work [9]. They might differ from the ones tested on the battery pack level, since the enclosure and interconnections affect the system thermal resistance and heat transfer effects, based on the various conductions and convections of the total system.

The simulation results are similar to the experimental ones: the temperature evolution on the hottest part of the module reaching up to 11.6 ^{o}C for the liquid-based cooling alone, and up to 7.4 ^{o}C for the hybrid solution is observed. It can be seen that the PCM contribute to the delay of the temperature rise but also to the temperature uniformity of the cells with 4^{o}C cell to cell difference without PCM compared to 2^{o}C difference with PCM. The delayed liquid cooling with the hybrid TMS can be in favor of the battery pack in BEVs for the longer operation time, as it can result to lower energy consumption by the pump for circulating the coolant. A simillar study is performed in [11] where authors compared the cost-efficiency between Al-based and PCM-based liquid cooling for battery modules, based on their total operating time and by activating/deactivating the cooling flow to preserve the cells within the SOA. A 26% lower consumption is observed by considering both the cooling cycling and the heating behavior of NMC-based battery topology at various flow rates. Lastly, a constant liquid flow scenario is evaluate in [11], where the cuycling experiment starts while the cooling is already activated. It is shown that for the high-energy prismatic, with approximately 2 times lower heat generation compared to SELFIE study case, a max 4^{o}C difference between the hybrid and the standalone liquid cooling is observed. This result also verifies our assumtpions for the performance evaluations of SELFIE pack.

Considering a higher ambient temperature, at 35^{o}C, the expected battery behavior stays within the SOA with the standalone liquid cooling of the same scheme, as illustrated in Fig.7.

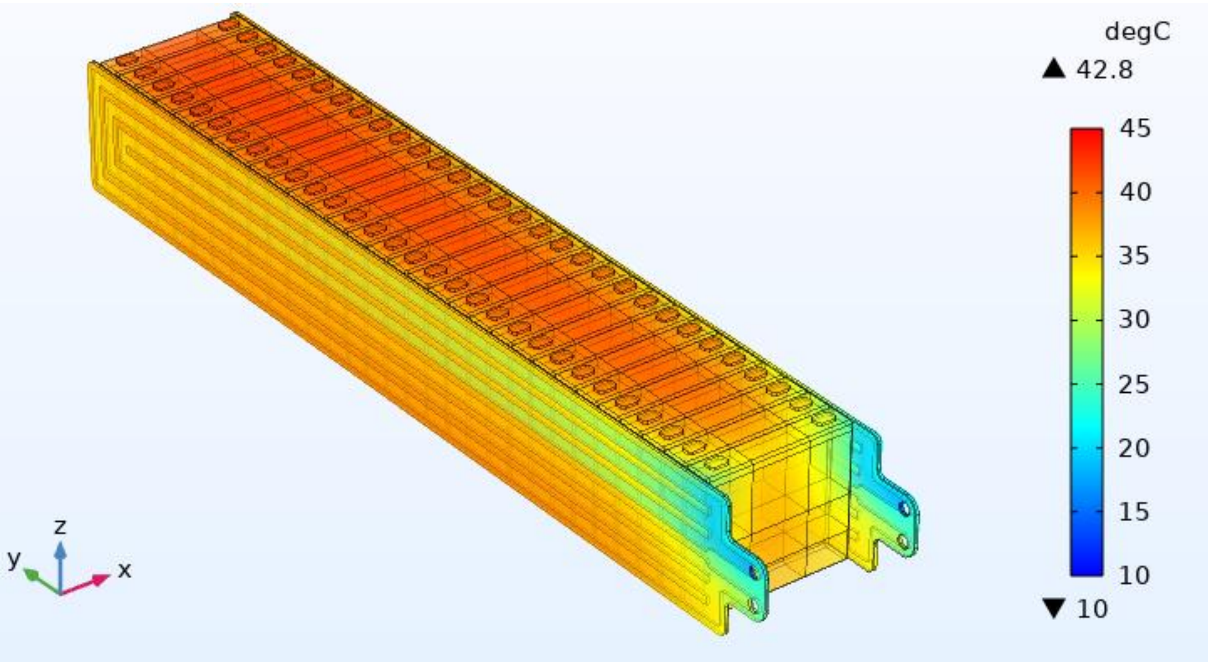


Figure 7: Numerical evaluation of thermal performance at fast charge between with only the liquid TMS at the elevated ambient temperature 35^{o}C

5 Conclusions

In this paper we presented the activities of SEFLIE project, which are related to a novel and self-sustained battery thermal management for EVs. The integration of the components to a full-scale battery system of approximately 30kWh is performed with two designs, and their performance is evaluated and assessed based on experimental and numerical analysis. The liquid cooling system alone can provide an adequate thermal control for the designed battery pack with the prismatic LTO battery cells already, and can accept the high cycling rates up-to 4C. The PCM-based TMS can contribute to the minimization of the temperature rate of change and support the heat uniformity in the pack. However, it is assessed in our system that the heat buffer is adding extra cost, reduces the gravimetric energy of the pack compared to the overall thermal benefit considering that the rest of the TMS system (i.e. liquid based TMS) remains unchanged. Considering the fact that the powerful liquid based TMS using newly developed slides plates already well cover the rather low heat dissipating LTO cells, the PCM-based TMS was not additionally integrated for further testing of the pack in the vehicle.

6 Future work

As the next step SELFIE project aims to integrate the individual components to the EV Fiat Doblo, as a use-case demonstration and validation. Further LCA analysis will be conducted to assess the cost-efficiency on the innovative components and the developed battery pack, from design to the full assembly.

Acknowledgments

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Presenter Biography

Dr. Theodoros Kalogiannis obtained his diploma degree in Electrical Computer Engineering and Energy Technology and his MSc degree in Wind Power Systems from DUTH and AAU respectively. He holds a PhD degree in the field of energy storage entitled as "Physical Optimization of Lithium-ion Battery Modules" obtained in VUB- Battery Innovation Centre, where he is currently working as a Post-Doctoral Senior Researcher. His expertise expands from lifetime testing and characterizing commercial battery cells, to design optimization of mechanical, thermal and electrical architectures of multi-cell topologies for various applications on the battery energy storage such as electric vehicles and grid support.