Primary and Secondary Vehicle Lightweighting Achieved by Acting on the Battery Thermal Management System

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Abstract. Global warming and air pollution are the main factors influencing international, national, and local strategies for the transition towards clean technologies to reduce polluting and climate-altering emissions. A further reduction of the latter can be achieved, with the same powertrain technology, by reducing vehicle consumption. One technique is to lighten the vehicle. The goal of this feasibility study is to act on the battery thermal management system to achieve vehicle lightweighting. Specifically, a sedan car with active-cooled batteries was considered as a reference case, and primary lightweighting was achieved through the use of passive cooling methods, i.e., air and Phase Change Material (PCM) cooling systems, followed by secondary lightweighting to re-establish the target range of the reference vehicle by downsizing the batteries. The air-cooled system leads to greater lightweighting, but its field of application is limited to vehicles operating in fleets; this obstacle can be overcome by using a PCM.

Keywords: Vehicle Lightweighting · Secondary Lightweighting · Traction Battery Thermal Management System · Energy Consumption · Electric Vehicle; PCM (Phase Change Material)

1 Introduction

Today, the topic of environmental sustainability is very important, in fact the reduction of polluting and climate-altering emissions is the main factor influencing international, national, and local strategies for the transition towards clean technologies. In addition to adopting more sustainable powertrains, such as electric ones, a further emission reduction can be achieved, with the same powertrain technology, by reducing vehicle consumption. The reduction in consumption can be achieved in various ways, such as through appropriate regenerative braking logics [1, 2], through the improvement of the power management logics (in particular regarding hybrid electric vehicles [3–5]), but also through the lightweighting of the vehicle [6, 13].

The battery pack plays an important role regarding environmental sustainability [7], Therefore, the study proposed here involves the analysis of different battery thermal

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management strategies to achieve both primary lightweighting, which will lead to a reduction in consumption and a consequent increase in the vehicle's range, and secondary lightweighting by reducing the number of cells in the battery pack, and thus its capacity, to restore the initial range of the reference vehicle. This work consists of a feasibility analysis rather than a precise modelling of the thermal management system of the battery pack. For the study, an active cooling system (with a total weight of 88.84 kg and an average power consumption of 815.5 W) was compared with two passive cooling systems: air and PCM (Phase Change Material) cooling systems.

2 Materials and Methods

The SedanCar from VI-CarRealTime, a consolidated state-of-the-art vehicle dynamics simulation tool, was chosen as a basis for the reference vehicle: an all-wheel-drive, electric passenger car equipped with two electric motors, one for each axle, with a total mass of 1986.6 kg. For this reference vehicle, a total consumption of the auxiliaries of 1500 W was also considered, including consumption related to the battery active thermal management system. The latter and the battery pack are those considered in studies [8–10]. In particular the battery pack is made up of 5664 cells of the NCA-18650 type, in 96S59P configuration (96 cells in series and 59 in parallel), with a capacity of approximately 56 kWh (162 Ah), an optimal operating temperature of approximately 20 °C and a maximum operating temperature of 60 °C. The active cooling system considered has a total weight of 88.84 kg, an average power consumption of 815.5 W, and it is sized to maintain an average refrigerant temperature of approximately 20 °C. Through VI-CarRealTime simulations, the torque and angular velocity time histories of the electric motors were obtained on WLTC (class 3b) driving cycle, which is considered the reference cycle. These outputs were then used as inputs for the TEST (Target-speed EV, Electric Vehicles, Simulation Tool) model described in [11], customized for this purpose, enabling to obtain the power demand that the vehicle system requires from the battery pack. Finally, this power demand has been used as input for a Simulink model, that simulate the battery pack and its thermal management system performance [8, 9].

The thermally managed battery pack model is simplified, in fact the aim of the work is a feasibility study and not an accurate thermal management modelling. It contains the "Datasheet Battery" model of the Simulink "Library Browser" [12]. This model takes as input the battery current, temperature, number of cells in parallel and in series in the battery pack, the rated capacity of a single cell, the cell open circuit voltage as a function of the battery State of Charge (SOC), the cell internal resistance, and the initial battery capacity. The outputs are instead the following: battery voltage, battery SOC, battery power (and power loss), and cell energy. The following equations were used for the battery pack thermal management model, where Eq. (3) is valid only if $\sigma \leq 1$, and (4) is valid for $\sigma > 1$.

$$Q_{CP} = K_{CP} \cdot (T_{bat\_prev} - T_{CP}) \tag{1}$$

$$T_{bat} = (Q_{bat} - Q_{CP}) \cdot dt/(\rho_{bat} \cdot v_{bat} \cdot c_{p,bat}) + T_{bat\_prev} \tag{2}$$

$$C_h = \left(2.04 \cdot \sigma^2 + 2.79 \cdot \sigma\right)/100 \tag{3}$$

$$C_h = (3.97 \cdot \ln\sigma + 4.83)/100 \tag{4}$$

Q_{CP} is the cooling heating power of the cooling plate of the thermal management system, Q_{bat} is the heat generated by the batteries and it is calculated as C_h multiplied by the battery power, T_{bat} is the average battery pack temperature, T_{bat_prev} is the average battery temperature relative to the instant of calculation preceding the one considered, T_{CP} is the average temperature of the refrigerant flowing in the heat exchangers, K_{CP} is the heat conductance at the cooling plate, ρ_{bat} is the average battery density, $c_{p,bat}$ is the specific heat capacity of the battery, v_{bat} is the total volume of the batteries, and, finally σ is the ratio between the battery power (expressed in kW) multiplied by 1 h and the battery power storage (expressed in kWh). Q_{CP} is imposed equal to zero for passive air-cooling system. Null is also imposed for PCM cooling systems until the melting point temperature of the PCM is reached, after that, the battery pack temperature remains constant until the heat generated by the battery pack does not reach the maximum heat absorbable by the PCM during the change of state, then the batteries temperature starts to grow again as in the initial phase.

Different sets of simulations are performed, composed of the repetition of WLTC cycles (class 3b), starting from SOC equal to 100% until the SOC drops below 20%, considering a simulation sample time equal to 0.01 s. The simulation sets are repeated with different battery pack initial temperatures.

3 Results

The study led to the choice of two materials as PCM: glycerol ($C_3H_8O_3$), with a melting point at 26 °C; and stearyl alcohol ($C_{18}H_{38}O$, 1-octadecyl alcohol), with a melting point at 57 °C.

Figures 1, Fig. 2, and Fig. 3 show, in the top, the trend of the battery State of Charge (SOC) with the succession of repeated WLTC cycles, respectively for the vehicle with passive air-cooled battery pack, passive glycerol PCM, and passive stearyl alcohol PCM cooled battery pack, starting from different battery pack temperature. In particular, in each graph, the vertical red lines separate one WLTC cycle from the next, and the horizontal green line represents the 20% of SOC. Similarly, the bottom of the figures shows the trend of the average temperature of the battery pack, and, in each graph, the vertical red lines separate one WLTC cycle from the next, and the dotted horizontal red line represents the maximum temperature limit, equal to 60 °C. As can be seen from Fig. 1, for an initial temperature of the battery pack from −20 to approximately 30 °C the limiting aspect for the vehicle is the capacity of the battery pack, i.e. the achievement of the SOC equal to 20%. Starting from 40 °C, however, the limit temperature of 60 °C was reached, in these cases it is therefore not possible to use the entire SOC range consecutively, it will be necessary to take a pause for cooling. As can be seen from Fig. 2, the behaviour of the vehicle with a glycerol PCM-cooled battery pack is similar to that found for the vehicle with passively air-cooled batteries.

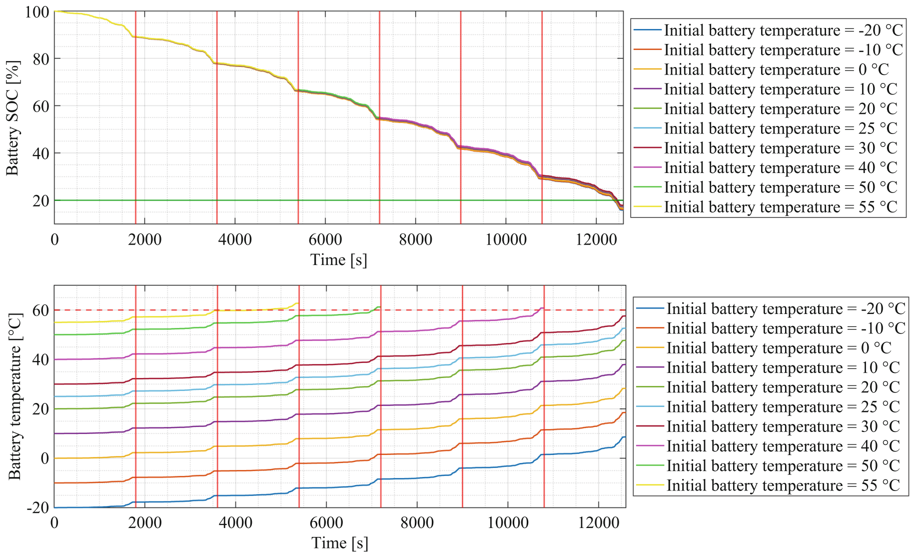

Fig. 1. Battery State of Charge (top), and battery pack average temperature (bottom). Passive air-cooled battery pack, in configuration 96S59P.

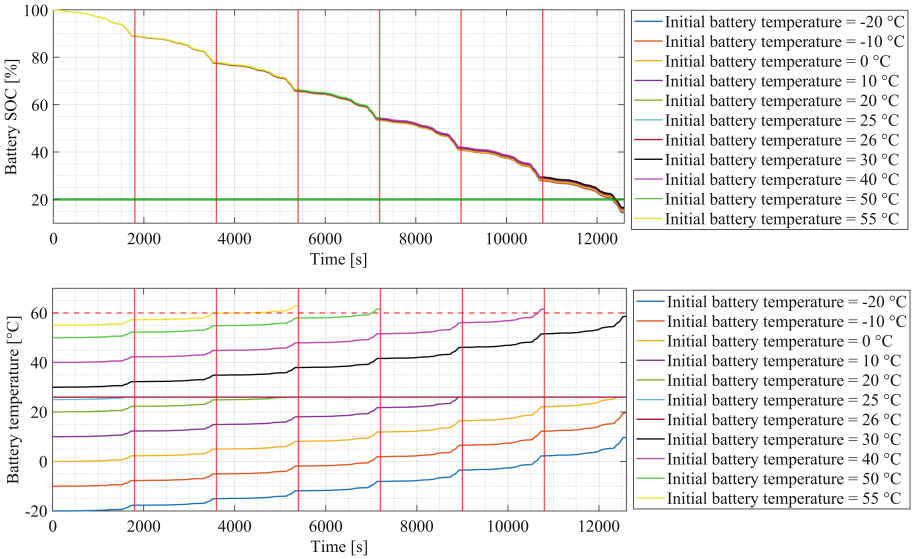

Fig. 2. Battery State of Charge (top), and battery pack average temperature (bottom). Passive glycerol PCM cooled battery pack, in configuration 96S59P.

Finally, as can be seen from Fig. 3, the stearyl alcohol PCM allows the vehicle to exploit the entire SOC range consecutively on the WLTC cycle, also starting from a battery pack temperature of 57 °C, the melting point temperature of this PCM.

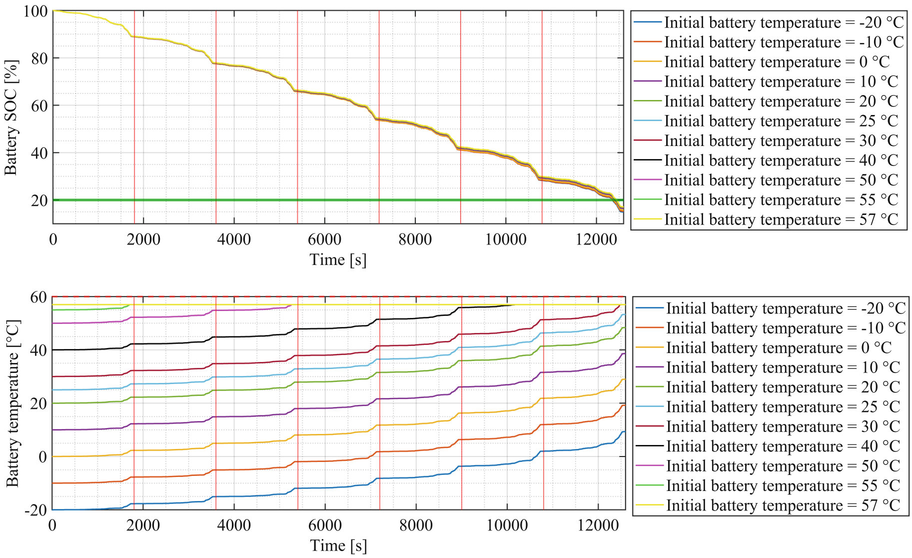

Fig. 3. Battery State of Charge (top), and battery pack average temperature (bottom). Passive stearyl alcohol PCM cooled battery pack, in configuration 96S59P.

As a secondary weight reduction measure, reducing the parallel cells of the battery pack from 59 to 54 was enough to achieve a range comparable to the one of the reference vehicle, for both air and PCMs cooled vehicles. This means removing from the battery pack 480 cells, for a total of 22.56 kg.

Table 1 resume the main results obtained in the study.

Table 1. Cooling system weight; primary and secondary lightweighting; and performance, in terms of energy consumption and vehicle range, on WLTC (class 3b) driving cycle.

System	Cooling system weight [kg]	Mass of cells removed [kg]	Primary lightweighting [kg]	Secondary lightweighting [kg]	Energy consumption [kWh/100km]	Range [km]
Active cooling	88.84	-	-	-	35.13	149.0
Air cooling	-	22.56	88.84	22.56	31.96	149.9
Glycerol	57.02	22.56	31.82	22.56	32.39	147.9
Stearyl alcohol	36.77	22.56	52.07	22.56	32.23	148.6

4 Conclusions

The air-cooled battery thermal management system is the simplest possible and leads to great potential for weight savings. However, it can be unsuitable for high starting temperatures of the battery pack. This issue also applies to the glycerol PCM-cooled system, which has however the added benefit of allowing the battery pack to operate near its optimal operating temperature for a longer time, thanks to its 26 °C melting point. Both systems suffer from the risk of excessive battery temperature rise but are suitable for vehicles operating in fleets with predefined and programmable missions. Finally, the stearyl alcohol PCM system is suitable for private use i.e. for less repetitive mission profiles and for varied driving styles, owing to its 57 °C melting point, although it sacrifices the ability to keep the batteries at an optimal operating temperature for longer periods.

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