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Integrated cooling/HVAC system design and control strategy for reconfigurable light electric vehicle

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Abstract

In the recent panorama, the use of conventional passenger vehicles has been discouraged from European level up to local municipalities. "Reconfigurable light electric vehicle" REFLECTIVE project targets at developing a light, fully electric vehicle capable of performing safely, efficiently, and multifacetedly in urban environments. By this way, it would be possible to fill the gap with the final user perception and electric vehicles market penetration. Moreover, in order to improve occupants' comfort, HVAC system has been considered as well, a feature which is not usually implemented in such a kind of vehicles. This paper will show results obtained for an integrated solution for cooling/HVAC circuits in terms of energy efficiency and occupants' comfort, with particular focus on proper battery operation. In fact, the battery thermal management is integrated into the HVAC circuit. The integrated circuit will take care of components' cooling so to guarantee proper operating conditions, HVAC for passenger comfort and battery thermal management so to assure proper operating conditions at the battery itself throughout different scenarios. Finally, the effectiveness of the control logic specifically developed for such an integrated circuit (HVAC/Cooling/Battery) will be shown in a urban driving cycle during winter season, so to maximize the heating loads both at powertrain and battery, with always assuring comfort conditions into the cabin.

Keywords: Cooling System; Battery Thermal Management; Electric Powertrain; HVAC System; Energy efficiency.

1. Introduction

The main features in terms of innovation of H2020 EU funded project REFLECTIVE have been already presented in a previous publication, Pippuri-Mäkeläinen et al. (2022) and, for sake of brevity, will not be presented here. Instead,

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this paper deals with the analysis, design and control strategy optimization of an innovative integrated cooling/HVAC system for the light electric vehicle under development. The main idea is to integrate the battery thermal management system with the HVAC used to guarantee comfort into the cabin, by picking up some conditioned air from the cabin or directly from the HAVC heat exchangers, to heat up/cool down the battery. In fact, for Li-ion batteries, the operating temperature should be kept within specific thresholds, in order to ensure high performance while preventing battery degradation, i.e. 15-40°C, Chiappini et al. (2019). Therefore, a specific control logic has to be implemented in order to contemporary assure occupants' comfort and battery optimal operation and life duration. In addition, due to the unavailability of waste heat sources, such as internal combustion engine thermal loads, a dedicated electric heater has to be included in the circuit. Nevertheless, in order to reduce energy consumption at the PTC branch, a recuperator heat exchanger has been considered, so to recover the available heat at the powertrain output. In particular, the hot coolant leaving the e-motor will be sent to the recuperator in order to heat up the liquid at the PTC branch and reduce battery energy consumption related to PTC operation. Results obtained in simulations are definitely encouraging and show the effectiveness of the proposed thermal loads management. In fact, significant energy savings can be achieved using the recuperator during driving, while the battery thermal management can be fruitfully fulfilled without the need of a specific circuit, through an effective use of conditioned air from the HVAC/cabin section.

Nomenclature

HVAC	Heat Ventilation and Air Conditioning
PTC	Positive Temperature Coefficient heater
egl505	ethylene glycol-water mixture (50/50 percentage mixture)
PID	Proportional Integrative Derivative controller

2. Methodology

The first steps of the activity have been devoted to the definition of the thermal loads and needs. In fact, the cooling circuit has to guarantee the proper operating conditions for a set of sub-systems, namely, conductive and wireless charging and powertrain assembly, while the HVAC system is used to guarantee both the comfort at the cabin, through a proper evaluation of all the loads, Mendecka et al. (2021), and the battery desired temperature maintenance. After having fixed all the needs and constraints for the different sub-systems, several circuit configurations have been analyzed. At the end, the circuit layout depicted in the following Fig. 1 has been proposed.

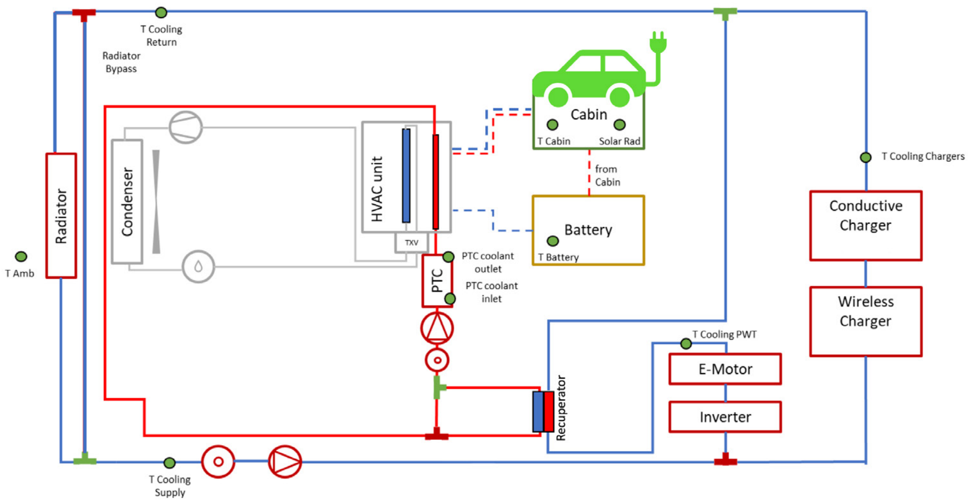


Fig. 1. Combined Layout configuration for REFLECTIVE cooling/HVAC systems.

The interesting features of the layout are next summarized. First, it is worth highlighting the presence of a radiator bypass branch which allows speeding up thermal transients during warmups. More in details, below a certain e-motor outlet temperature, the coolant flow will not pass through the radiator but rather through the above mentioned bypass. This way, no activation of the radiator fan will occur, with apparent benefit in terms of energy consumption.

Secondly, due to the lack of heat rejections typical of traditional propulsion systems, a PTC circuit must be considered in order to allow for cabin heating during winter. Thus, a recuperator (red and blue rectangle in Fig. 1) has been implemented to recover part of the heat available at powertrain outlet section. This way, in fact, the hot coolant at e-motor will pre-heat the coolant entering the PTC circuit, with subsequent reduction in energy consumption at heater (PTC) section. Moreover, this heat exchanger has another positive effect due to the reduction of e-motor outlet egl5050 temperature which in turns reduces the number of occurrences of radiator fan activation, with evident benefits in terms of energy consumption.

Finally, the battery thermal management will be carried out via the HVAC system as well, allowing for a highly integrated design, reducing the number of involved components. A specific control logic has been implemented in order to fruitfully use the hot/cold air produced at the HVAC block in order to keep the battery into an acceptable temperature range. More in details, battery heating can be realized via the hot air present into the cabin, while the battery cooling can be obtained through the fresh air at HVAC block – without entering the cabin. It is worth pointing out that in the case of battery heating no side effects on cabin temperature will occur, while some temporary misalignments can be observed with respect to the cabin comfort in case of battery cooling, due the higher priority of the battery thermal management.

3. Vehicle Model Description

In order to properly evaluate the heat rejections of the powertrain components, a self-made simulator, developed in Matlab/Simulink, is used Tribioli et al. (2015), which consists of a quasi-static forward-looking model of the entire vehicle. The vehicle is a L7 e-CU heavy quadricycle, with a curb weight of 600 kg without the battery pack, as per the EU Regulation No 168/2013.

The overall model structure includes three principal blocks:

- Driver block: this block returns the acceleration and brake pedals control signals determined by means of a Proportional-Integral-Derivative (PID) controller. These signals are used to adjust the feedback signal of the actual vehicle speed over the targeted desired value;
- Powertrain block: this block receives the instantaneous torque/speed demands to the powertrain, as a function of the brake/accelerator pedals signals and kinematic relations at the transmission. As a consequence, the power consumptions and heat rejections of the powertrain components and state of charge profile are computed, taking into account their physical limits;
- Vehicle block: this block computes the effective vehicle speed as a function of the traction/brakes torque inputs from the powertrain by solving the longitudinal vehicle dynamics equation. To solve this equation, a drag coefficient of 0.3 and a vehicle frontal area of 2.17 m^2 have been used, while the rolling resistance coefficient has been estimated considering a tire pressure of 2 bars.

A PID controller is used in the Driver block to derive the accelerator $\alpha(t)$ and brake $\beta(t)$ pedals signals by means of the following equation:

$$p(t) = k_P e(t) + k_D \frac{de(t)}{dt} + k_I \int_{t_0}^{t_f} e(t)dt \tag{1}$$

Instead, the Powertain block contains the powertrain components models, i.e. e-motor, battery, inverter, in order to take into consideration their physical limits and verify the possibility to accomplish the vehicle mission, while evaluating power consumption and state of charge profile. In particular, the e-motor is modeled by means of a stationary efficiency map and maximum/minimum torque curves, the battery is modeled by means of a 0-th equivalent circuit model, while the inverter is modeled as a constant efficiency.

For the estimation of the inverter instantaneous power losses $\dot{Q}_{INV}$ as a function of the inverter output power P_{INV} the following equation has been used:

$$\dot{Q}_{INV} = P_{INV}(1 - \eta_{INV}) \quad (2)$$

Where for the efficiency η_{INV} a constant average value equal to 98% has been used.

The instantaneous efficiency of the electric machine η_{EM} is evaluated as a function of its torque T_{EM} and angular speed ω_{EM}, as per the following:

$$\eta_{EM} = f(\omega_{EM}, T_{EM}) \quad (3)$$

And the instantaneous thermal load of the e-machine $\dot{Q}_{EM}$ is estimated by using the following equation:

$$\dot{Q}_{EM} = P_{EM}(1 - \eta_{EM}) \quad (4)$$

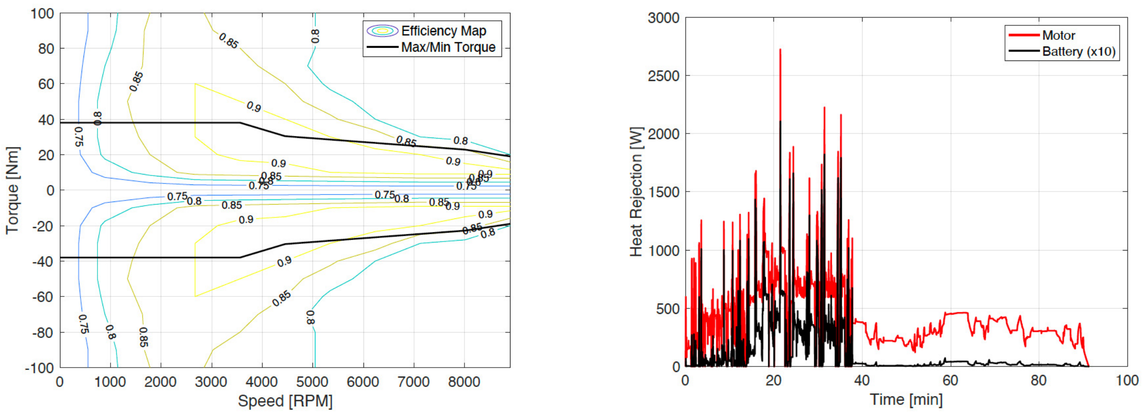
Finally, the battery voltage V_L is evaluated by means of the well-known Kirchhoff law, as given by:

$$V_L = V_o - IR_o \quad (5)$$

Where V_0 is the open circuit voltage and R_0 is the equivalent internal resistance, which considers the ohmic losses through the battery components. In this study, the cooling circuit of the battery is designed to be able to maintain the battery at a constant temperature, therefore the dependence of open circuit voltage and internal resistance on temperature can be neglected Plett at al., 2006. The thermal load of the battery is thus estimated as a pure resistive ohmic loss, as shown in the following equation:

$$\dot{Q}_{batt} = I^2 R_o \quad (6)$$

For non-disclosure reasons and for the purpose of the present study, which is the assessment of the effectiveness of proposed integrated cooling/HVAC circuit solution, the e-motor efficiency map and torque curves, shown in Fig.2 (a), have been assumed so as to be similar but not identical to the ones the original e-motor, while the battery open circuit voltage and internal resistance curves as a function of the state of charge have been derived from data of a Li-ion battery cell manufactured by A123 available in literature, Lee et al., 2018, and adjusted in order to achieve performance similar to the project battery pack. Simulations have been performed for a real-like driving cycle created in the project to represent a typical speed profile in Helsinki area. This cycle is characterized by an initial extraurban-like part of roughly 38 min, that allows reaching a maximum speed of 90 km/h, as per vehicle homologation constraint, and a second urban-like part of around 60 min with a maximum speed of 45 km/h. Finally, Fig.2 (b) provides the heat rates for the battery and e-motor along this prescribed driving mission.



(a) (b)

Fig. 2. Performance map and curves for the modeled e-motor (a) and Motor and battery heat rejections for e-motor and battery (b)

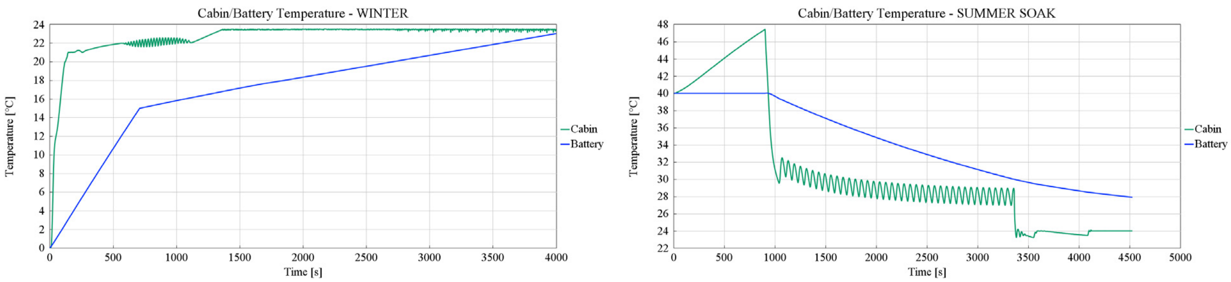
4. Control Logic Verification

In this section the control logic developed within the project execution will be firstly tested in constant speed test cases both in winter (0°C ambient temperature) and summer (40°C ambient temperature) conditions with running the vehicle at constant speed (50km/h) and under the maximum load at both e-motor and inverter. In other words, a kind of worst-case scenario has been considered in order to highlight the capabilities of the developed strategy, which integrates both cooling and ventilation purposes. The following Table 1 summarizes the simulations parameters used for this preliminary assessment.

Table 1. Operating parameters adopted for control logic verification.

Operating Parameter	Winter	Summer
Vehicle Speed [km/h]	50	50
Soak Phase [s]	0	900
Ambient Temperature [°C]	0	40
Ambient Humidity [%]	95	45
Solar Radiation [W/m2]	0	1000
Cabin Target Temperature [°C]	23	24

As one can observe from Table 1, for the summer scenario a soak phase is considered as well. This condition simulates the car parked under the sun before it is started. Due to this stop, temperature inside the cabin will significantly rise and the HVAC system will be overloaded, due to the contemporary requests of both battery and cabin. This represents a quite harsh operating condition, but it will allow to validate the proposed logic. Results will be shortly presented in the following figures with particular focus on temperature evolution in both battery and cabin.



(a) (b)

Fig. 3. Comparison of cabin and battery temperature during winter (a) and summer (b) driving scenarios.

From Fig. 3 one can notice how the temperature at both cabin and battery falls into an acceptable range. As previously anticipated, for the winter scenario Fig. 3(a), no particular issues arise for both the cabin and the battery. In fact, the conditioned air into the cabin has been sent to the battery in order to slightly heat it up. During the first phases of winter scenario, an internal pre-heating is considered as well, with the aim of rapidly increasing the battery temperature to an acceptable value (about 15 °C). On the other hand, the summer scenario clearly highlights the priority given to the battery while cooling is required. From Fig. 3(b) one can observe how, after the initial soak phase (vehicle parked under the sun), the battery has the priority, and the cabin is only partially chilled (temperature in the range of 28 °C). After having reached optimal conditions at the battery, the cabin can be finally chilled with reaching the target value of about 24 °C. The showed results indicate that the control logic is capable to deal with both winter and summer scenarios. Thus, in the next section, the model will be tested in a dynamic test like the driving cycle specifically designed within the REFLECTIVE project.

5. Helsinki Driving Cycle

In this section, the results obtained in the Helsinki driving cycle, opportunely designed within the project execution, will be presented for the winter scenario. The aim of this activity is to point out the benefit of the recuperator with comparing the same driving cycle both with and without the recuperator. Such a heat exchanger, in fact, allows reducing the energy consumption at the PTC branch and at the radiator fan. Instead, the summer scenario will not be considered as only battery/cabin cooling are required and the PTC is obviously always off. Winter operating conditions are the same of Table 1, except for the velocity profile which is the one related to Helsinki driving cluster. The next Fig. 4 reports the integral of energy evolution within the driving cycle.

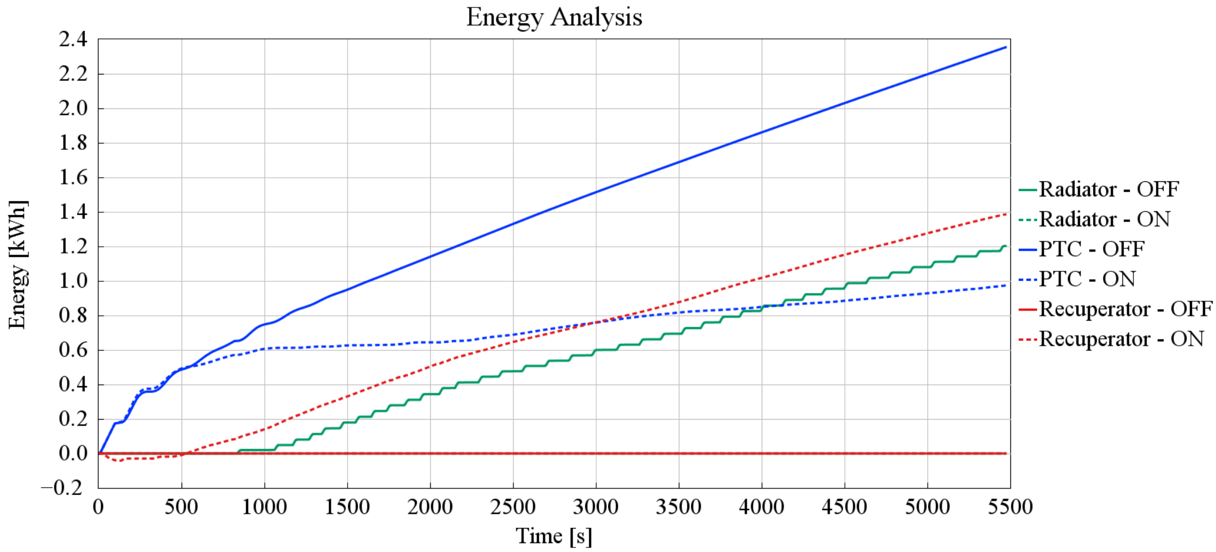


Fig. 4. Integral energy evolution at different interesting components within the urban driving cycle without (solid line) and with (dashed line) recuperator.

From Fig. 4 one can note the effectiveness of the recuperator. In fact, looking at the two blue curves it may be pointed out how the energy required at PTC has been drastically reduced with introducing such an additional heat exchanger. Moreover, the two green lines show how the recuperator presence allows reducing the use of radiator, and of its fan, therefore. The e-motor outlet temperature, on the main branch, is reduced because of the heat exchanged at the recuperator. Consequently, the main flow can pass through the radiator bypass with apparent benefit from an energetic point of view. However, the main effect of the recuperator is the reduction of heat/power required at the PTC used for heating up the cabin. The comparison of the two strategies can be further carried out with referring to the next Table 2, where the results are synthetically reported.

Table 2. Energy consumption/saving [kWh] at final time of Helsinki driving cycle.

Component	Without Recuperator	With Recuperator	Delta
Recuperator	0.00	1.39	+1.39
PTC	2.36	0.98	-1.38
Radiator	1.20	0.00	-1.20

Additionally, the next Fig.5 reports the temperature evolution both at e-motor outlet and at PTC inlet. These two quantities are indirectly linked due to the presence of the recuperator, which ideally connects the main branch for powertrain cooling with the inner PTC loop for cabin/battery heating.

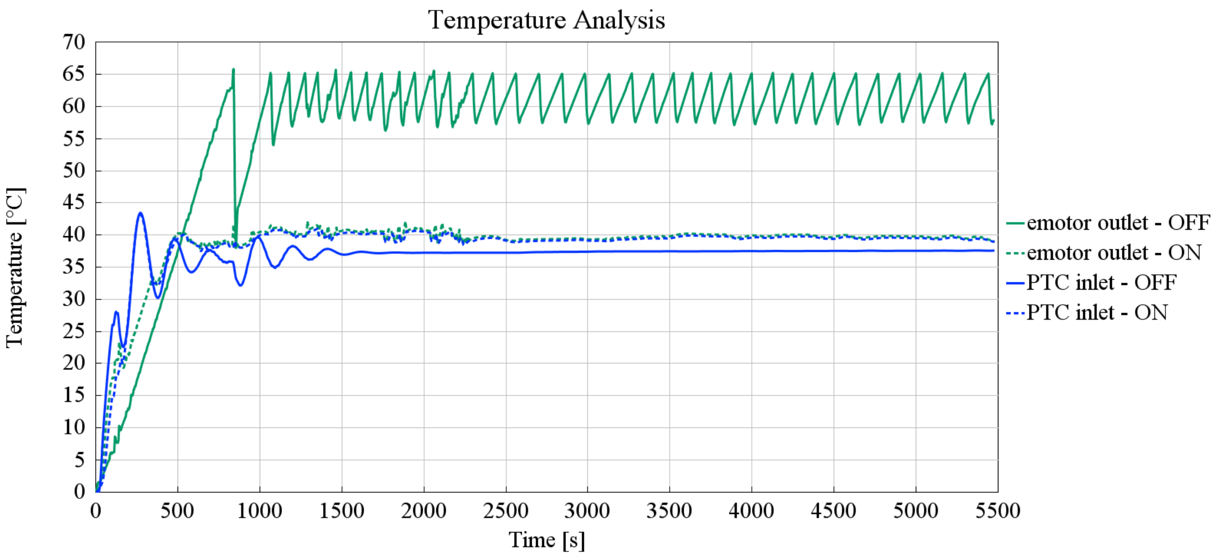


Fig. 5. Temperature analysis at e-motor outlet and PTC inlet within the Helsinki driving cycle without (solid line) and with (dashed line) recuperator.

As one can note, e-motor outlet temperature when the recuperator is disabled is significantly higher than the value reached when the recuperator is used. Moreover, in the recuperator off condition, the e-motor outlet temperature requires the activation of the radiator branch and subsequently of its fan, in order to cool down the coolant. Vice versa, while the recuperator has been activated, the e-motor outlet temperature is always below the radiator activation threshold, allowing the coolant passage only throughout the bypass branch. Additionally, the delta temperature in between e-motor and PTC is of about 20 °C when the recuperator is deactivated, while it practically vanishes once the recuperator is on.

Finally, the effectiveness of the above mentioned strategy can be also confirmed while looking at battery/cabin temperatures during driving cycle, as reported in the next Fig. 6. In fact, no deviations for these quantities can be observed while comparing the two considered recuperator activation strategies.

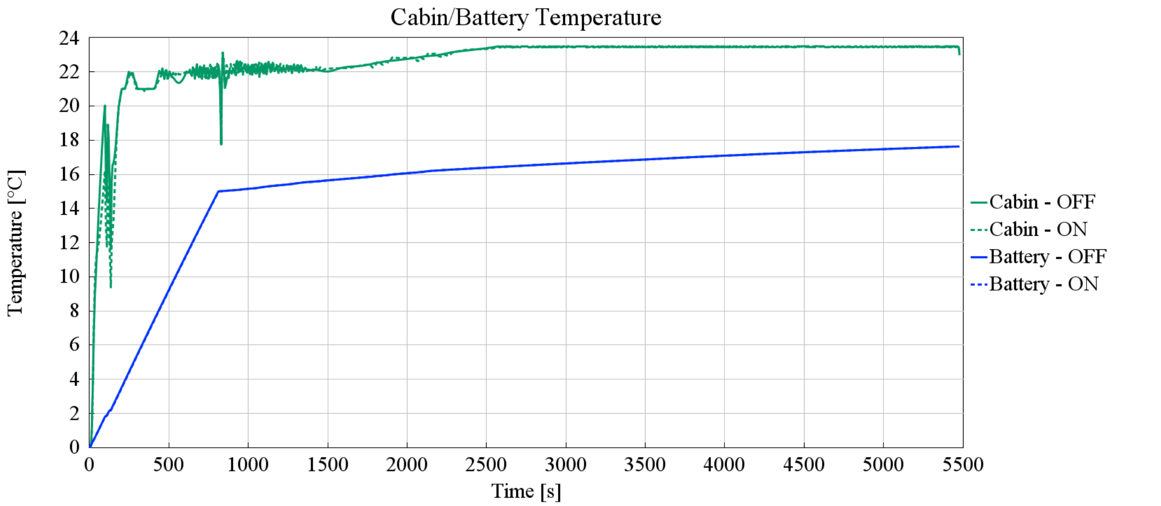


Fig. 6. Temperature analysis at cabin and battery within the Helsinki driving cycle without (solid line) and with (dashed line) recuperator.

6. Conclusions

This paper has demonstrated the capability of the proposed circuit coupled with an ad-hoc control strategy to deal with the contemporary needs of cooling, cabin comfort and battery thermal management. The strong interaction between the different circuits asked for a dedicated strategy, capable to consider several inputs from different components. Moreover, the possibility to use HVAC potentialities for taking care of the battery thermal management has driven to an accurate control logic definition in order to deal with heating/cooling needs at the battery, which always has the priority, without significantly penalizing the cabin comfort. In addition, the presence of a recuperator, bridging the primary cooling circuit with the inner PTC loop strived to a significant reduction of energy consumption both at the PTC itself, but also at the radiator as well. The activity has been carried out in the framework of H2020 funded REFLECTIVE project with the aim of developing an innovative and energy efficient cooling/HVAC integrated system. This represents the first step after which the developed circuit will be implemented on a vehicle in real operating conditions which hopefully will confirm the results obtained so far.

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