DRIVEMODE

Integrated Modular Distributed Drivetrain for Electric & Hybrid Vehicles

Document title: DRIVEMODE - Results analysis and final report and/or scientific publications

D5.4: DRIVEMODE - Results analysis and final report and/or scientific publications
WP 5, T 5.4

Authors: Laura Tribioli (SCIRE)

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DRIVEMODE

Technical references

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Task	T5.4 - Simulations and Result Analysis
Lead beneficiary	SCIRE
Contributing beneficiary/ies	NEVS
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* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

v	Date	Comment	Author	Beneficiary
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Executive Summary

The purpose of the deliverable is to provide information about the simulations of the system for the evaluation of the performances of the chosen final design of the cooling circuit.
This deliverable is linked to Task 5.4 *Simulations and Results Analysis*, which is aimed at the evaluation of the effectiveness of the vehicle cooling circuit operation under different scanarios. Simulations are made by means of the model realized within Task 5.3 *Cooling circuit layout definition and sizing* and presented in D5.3 *System modelling for the evaluation of the final design*, based on the vehicle platform provided by NEVS and data collected from partners during Task 5.2 *Data collection from other WPs* and reported in D5.2 *Thorough data collection from other partners and WPs and further analysis to build up a database*.
The baseline vehicle platform includes cooling circuit components and functionalities to which the new IDMs must be adapted.

1. The Task started at M23 and is going to end on M27. D5.4 "Results analysis and final report and/or scientific publications" is due by January 31st, 2020.
2. This activity represents the **cooling circuit simulation** and is being used to **verify the effectiveness of the system control strategy** to manage the overall circuit cooling under the constraints on maximum allowable temperature and minimum volume flow rate.

Attainment of the objectives and if applicable, explanation of deviations

The deliverable reports the activity carried out during the simulation of the cooling circuit operation in different scenarios and represents the final report of the activities conducted within the Work Package 5 on the Cooling Circuit. In particular, the expected final output of Task 5.4 and of the entire WP5 should have been a thorough analysis of all the results obtained in the simulation campaign, exhaustive enough to provide useful and reliable data for all the related WPs.
To this aim, different operating conditions have been simulated for in-depth analysis of the system behaviour. GT-Suite has been used for transient simulations. The cooling system model has been integrated to a zero dimensional model of the entire vehicle, to simulate different driving missions, while the effectiveness of the cooling system in elevated temperature conditions has been estimated thanks to the precision of the one-dimensional model.
The objectives defined in Task 5.4 have been thus attained and major results are reported in this deliverable.

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Introduction

The aim of WP5 is to design and evaluate the cooling circuit performance of the integrated vehicle system, under the of minimum number of cooling elements, in order to design a single cooling circuit for all devices.

- The first part of the WP5 is the collection of useful data coming from other WPs,
- which will be used as input for the second stage of the WP5, where the integrated cooling circuit has to be simulated.

At the end of the setup process a robust model of the vehicle cooling circuit has been delivered, with the aim of simulating and verify the system operating conditions.

The cooling circuit basic concept has been defined in D5.1 Documentation of the basic concept of the cooling circuit [1].
Internal activities of the Thermal Team of NEVS had lead to the final layout of the cooling circuit, whose complete schematic is provided in Figure 1.

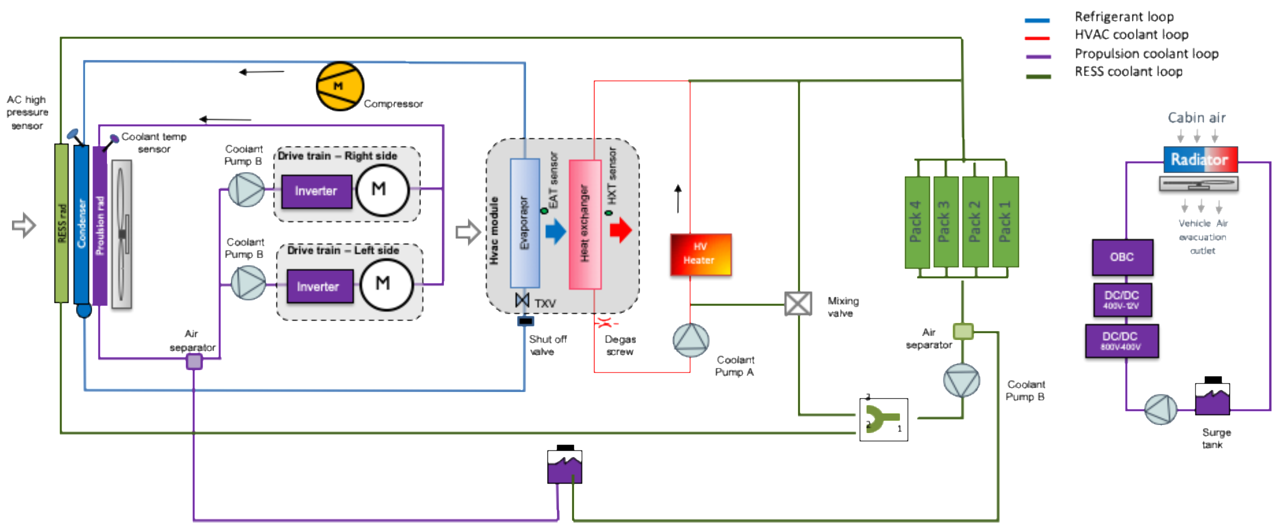

Figure 1. Thermal Schematic Layout for the DRIVEMODE demonstrator

As one can note from the figure, there exist four separate circuits:

1. Refrigerant loop
2. HVAC coolant loop
3. Propulsion loop
4. RESS coolant loop

For the cooling of OBC and 400V-12V DC/DC and 800V-400V DC/DC there is a separate loop, representend on the right of the figure. The others loop are all highly integrated. WP5 is focused only on the **propulsion coolant loop**, which, however, is influenced by the HVAC/Refrigerant circuit through the condenser and by the RESS circuit through the RESS radiator. Moreover, it must be recalled that the system operation is subject to the following contraints:

- Max Coolant temperature: 65 °C
- Min Flow rate@ maximum power: 10 l/min for each IDM

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Cooling Circuit Model

The circuit model has been thoroughly presented in D5.3 [2] and is shown in Figure 2.

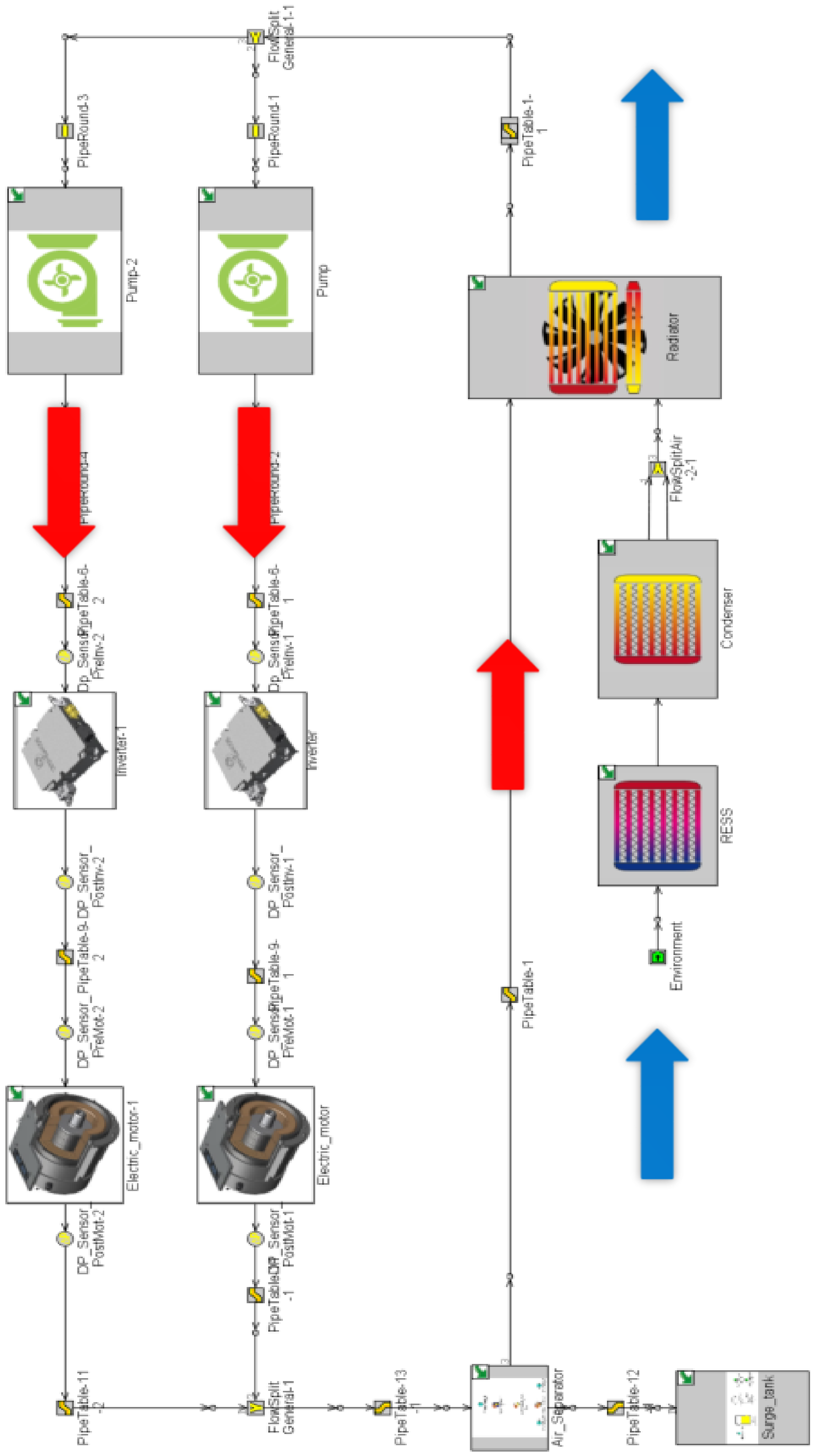

Figure 2. Circuit schematic - Sketch from GT Suite model

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For the estimation of the thermal loads of inverter and electric machine, as already reported in D5.3, the power losses $\dot{Q}$ have been calculated as a function of the instantaneous component power P, with the following equations:

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

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

Where for the inverter efficiency η_{INV} a constant average value equal to 97% has been used. This value results in being a bit conservative with respect to the expected one.

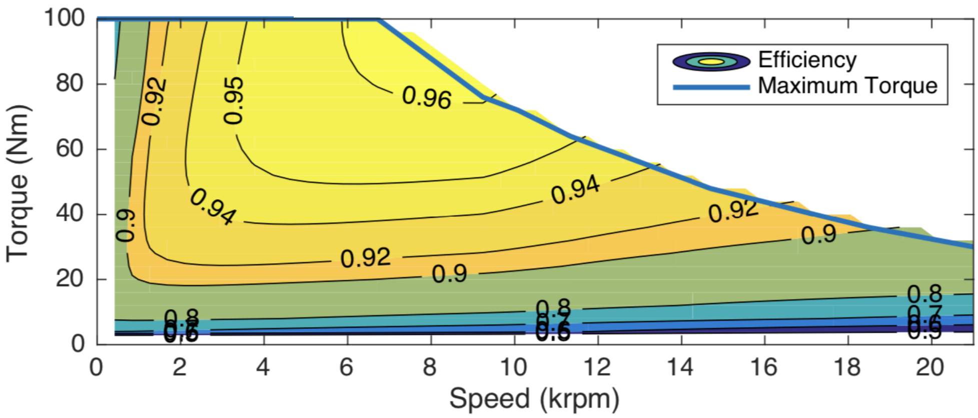

Figure 3. Efficiency map of the e-machine

Thermal load of the e-machine is instead evaluated by means of the efficiency map of the e-motor - provided by UL (WP3) and shown in Figure 3.

For the other components the following assumptions apply:

(a) the thermal load of the propulsion radiator is obviously an output of the analysis rather than an input. All the data needed to model the heat transfer behavior of the radiator have been provided by NEVS.

(b) thermal loads in hoses and pipes is zero. All the data needed to model the heat transfer behavior of the pipes have been provided by NEVS.

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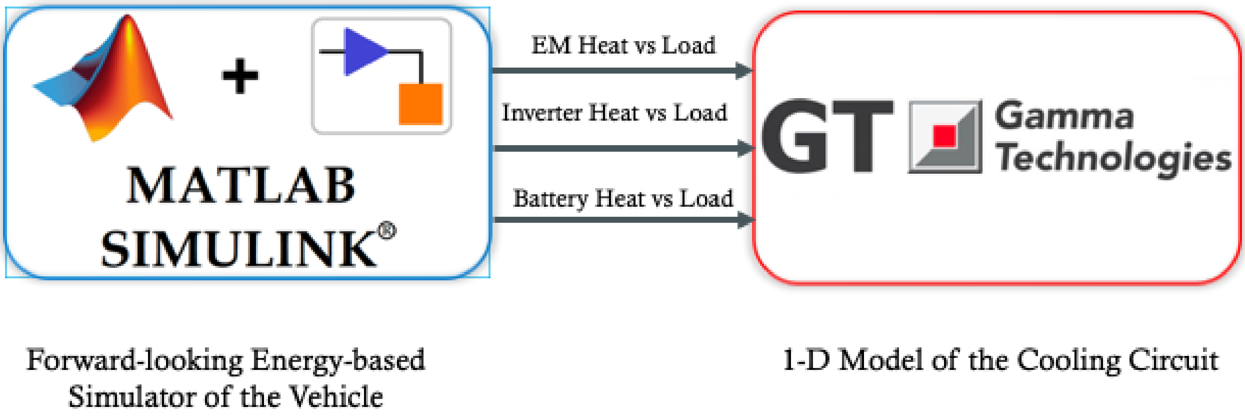

Figure 4. Sketch of the cooling circuit modeling process

In order to properly evaluate the motor efficiency as a function of the instantaneous operating conditions, a self-made simulator, developed in Matlab/Simulink, has been used. The heat rejection profiles obtained for each component are then used as input for the GT-Suite model, as shown in the schematic provided in Figure 4.
The tool consists of a quasi-static forward-looking model of the entire vehicle. The employment of such a tool allows for a more realistic evaluation of the energy conversion chain in the vehicles, commonly evaluated by means of backward-facing models. In fact, the main weakness of a backward-looking approach is that the speed trace is assumed to be always met. Thus, it evaluates a torque demand which can be different from the torque actually needed to follow a speed trace, e.g., during accelerations. The used forward-facing simulator includes a driver's model based on a PID controller, steady-state performance maps for the e-machines, a zero-dimensional equivalent circuit model for the battery, and computes vehicle velocity by solving the longitudinal dynamics of the vehicle.

The vehicle used in simulations is the NEVS 9-3 SEDAN vehicle, whose main basic parameters and performance indicators are listed in Table 1 and have been retrieved form D2.1 [5] and D2.2 [6].

Table 1. Characteristics of the reference vehicle

Basic Parameters	
Gross Weight Vehicle	2160 kg
Vehicle frontal cross-section	2.618 m^2
Aerodynamic drag coefficient	0.29
Tire rolling resistance (dry asphalt)	0.02
Wheel radius	0.335 m
Performance Indicators	
Acceleration from 0 to 50 kmph	5.5 s
Acceleration from 0 to 100 kmph	12 s
Maximum climbing at 80 kmph	12%
Maximum climbing at 130 kmph	4%
Maximum Speed	150 kmph

Existing battery pack of 400 V DC is not applicable for the demonstration vehicle. Main characteristics for the 800 VDC battery system which will be used in the demonstration vehicle for

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DRIVEMODE project are listed in Table 2. The 800 VDC battery system is under NEVS internal development program and data are not available for the system modeling.

Table 2. Battery pack main characteristics

Operating Voltage (Max/Nominal)	796/720 VDC
Operating Current (Max/Nominal)	280/140 A
Battery Capacity	46 kWh

Therefore, for the battery performance a zero-th order equivalent circuit model has been employed to evaluate the battery heat rejection as following:

$$\dot{Q}_{batt} = I^2 \cdot R_0(SoC) \quad (3)$$

with the battery current I calculated as a function of the battery opern circuit voltage V_{OC} the power request P_{batt} and an equivalent internal resistance $R_0(SoC)$, function of the state of charge (SoC):

$$I = \frac{V_{OC} - \sqrt{V_{OC}^2 - 4P_{batt}R_0}}{2R_0} \quad (4)$$

A WLTC scenario has been simulated in order to verify the effectiveness of the control strategy of the cooling system.

In particular, the same control strategy used in the existing vehicle has been chosen for the demonstration one. This assumption has been done mainly for its robustness and reliability, related to the fact that it has been already used and tested.
In the meantime, the design of a novel control strategy has been carried out, concluding that it is not safe to implement it on the vehicle due to the lack of experimental data on the air mass flow through the radiators at different conditions, which might affect its proper calibration.
In fact, the description of the air mass flow and velocity through the radiators and/or underhood flow calculations with regard to IDM compartment would require several data and an insufficient amount of details can result in incorrect air flow quantities through different heat exchangers and fan, hence leading to incorrect results for the simulation in total.

In the existing vehicle, the pump speed is linearly increased as the coolant temperature at the radiator inlet increases, while the fan is kept off until this temperature is below 60°C. For higher values, it is switched on at its maximum capacity (i.e. input signal equal to 90%).
The linear dependency of the pump speed (equivalent to the pump flow rate) on the coolant temperature at the radiator inlet for the demonstration vehicle is provided in Figure 5. It goes from a minimum of 10 l/min as per the project constraint to a maximum flow rate equivalent to the operation of the pump at its maximum speed.

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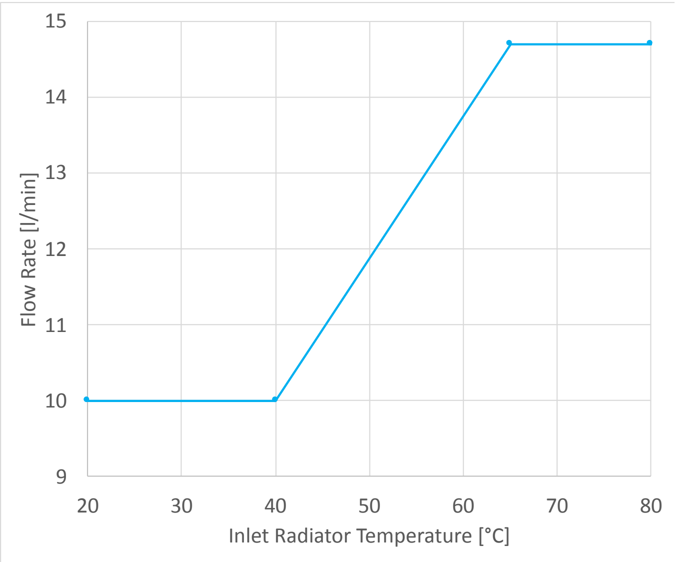

Figure 5. Pump flow rate as a function of coolant temperature at the radiator inlet

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WLTC Scenario

The control strategy effectiveness has been test over the WLTC standard driving cycle, shown in Figure 6, under the following additional assumptions:

1. Gear box efficiency: 0.97
2. Inverter Average Efficiency: 0.97
3. Gross Weight for the Vehicle
4. Condenser heat rate: 0 kW
5. Ambient Temperature: 40°C
6. Coolant Initial Temperature: 40°C

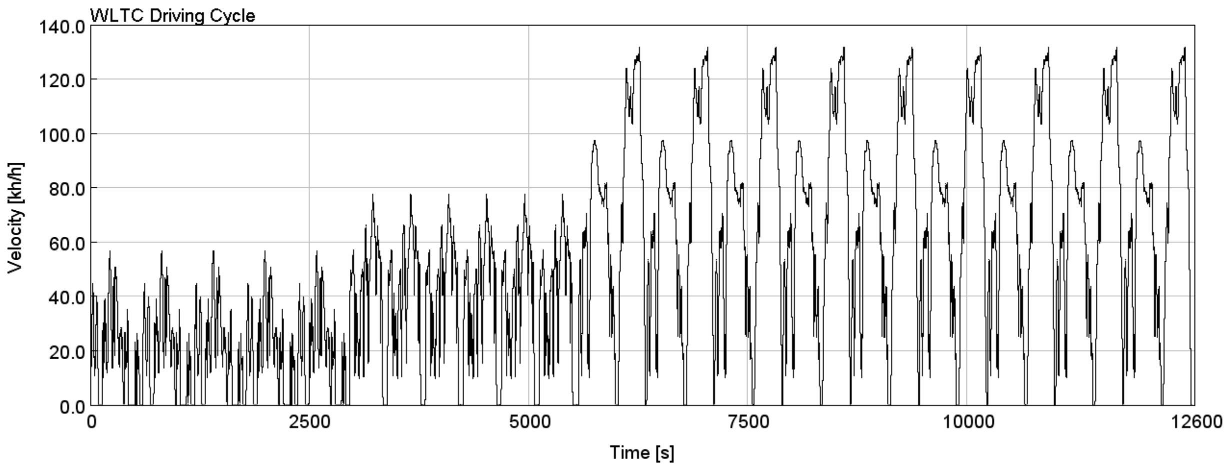

Figure 6. WLTC Speed Trace

In order to obtain reliable results, the simulations have been performed in transient mode. In particular, the speed trace and heat rejection profiles as a function of time have been directly used in the GT-Suite model.

Figure 7 and Figure 8 show the heat rejections of the motor, inverter and battery with respect to time. As one may note, there is a correspondence between the velocity profile and the heat rejection, which is obviously affected by the road load. These plots are mostly provided to prove the soundness of the 0D vehicle simulator. Those heat rejections have been calculated as explained in the previous Section and, in particular, with the set of Equations from (1) to (4).

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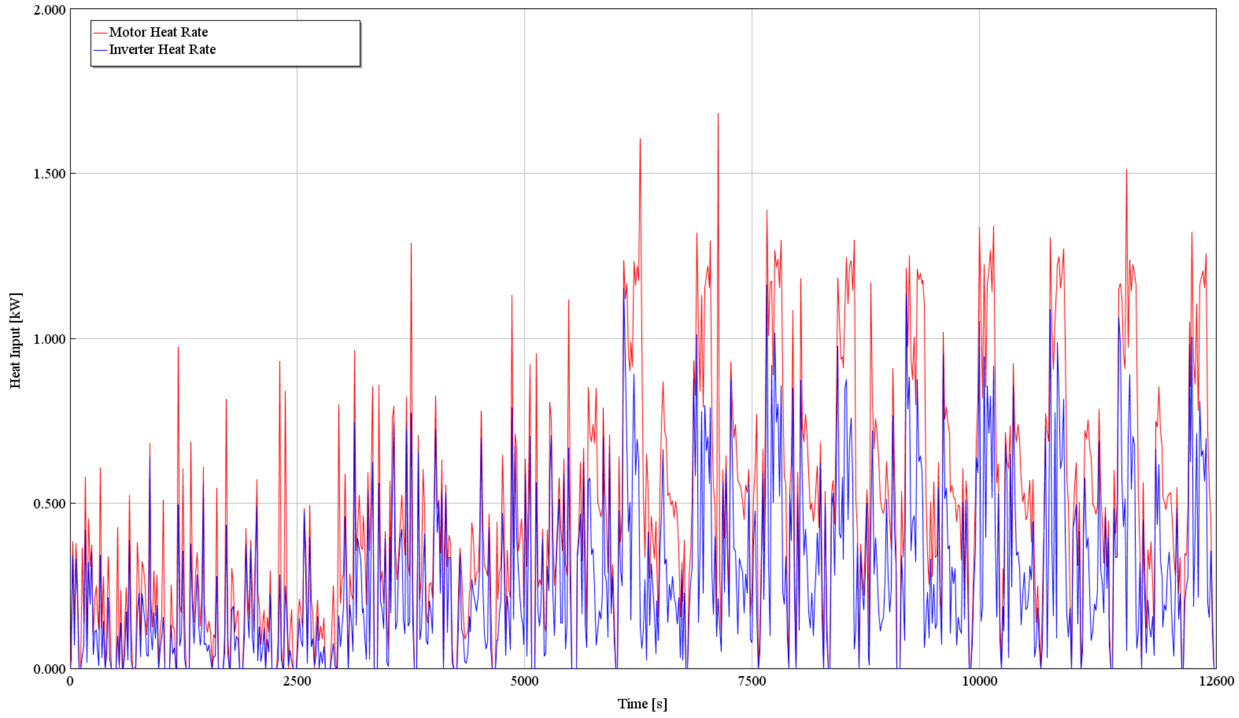

Figure 7. Motor and Inverter heat rejections vs time

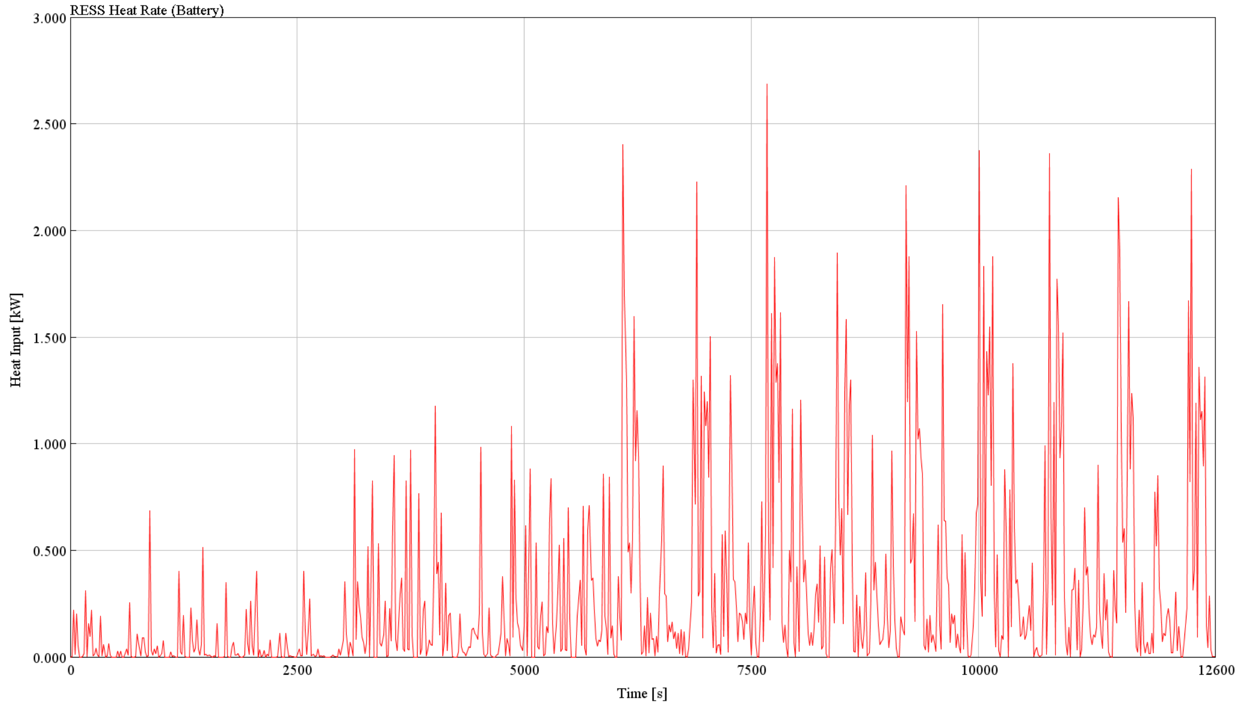

Figure 8. Battery heat rejections vs time

Figure 9 shows the coolant temperature at radiator inlet and the coolant volumetric flow rate through one pump with respect to time. These results have been obtained with the 1D cooling circuit model, employing the heat rejections provided in Figure 7 and Figure 8 as inputs. As one can note, the project constrains mentioned in the Introduction are always met as the coolant

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temperature never overcomes 65°C while the coolant volumetric flow rate across each pump nevers goes below 10 l/min.
It is immediate to observe the correspondence of the volumetric flow rate with the coolant temperature as per the control strategy shown in Figure 5 and, since the temperature of the coolant is always lower than 60°C, the fan is never switched on. It is also worth noting that, at the very beginning of the driving cycle, characterized by low vehicle speeds, the coolant temperatures are the highest. In fact, if on one hand the low thermal loads of the components (see Figure 7 and Figure 8) would correspond to a low coolant temperature, on the other hand the very low mass flow rate of the air passing through the radiator, dramatically affects the heat removal from the coolant and a higher pump speeds are required to compensate this effect.

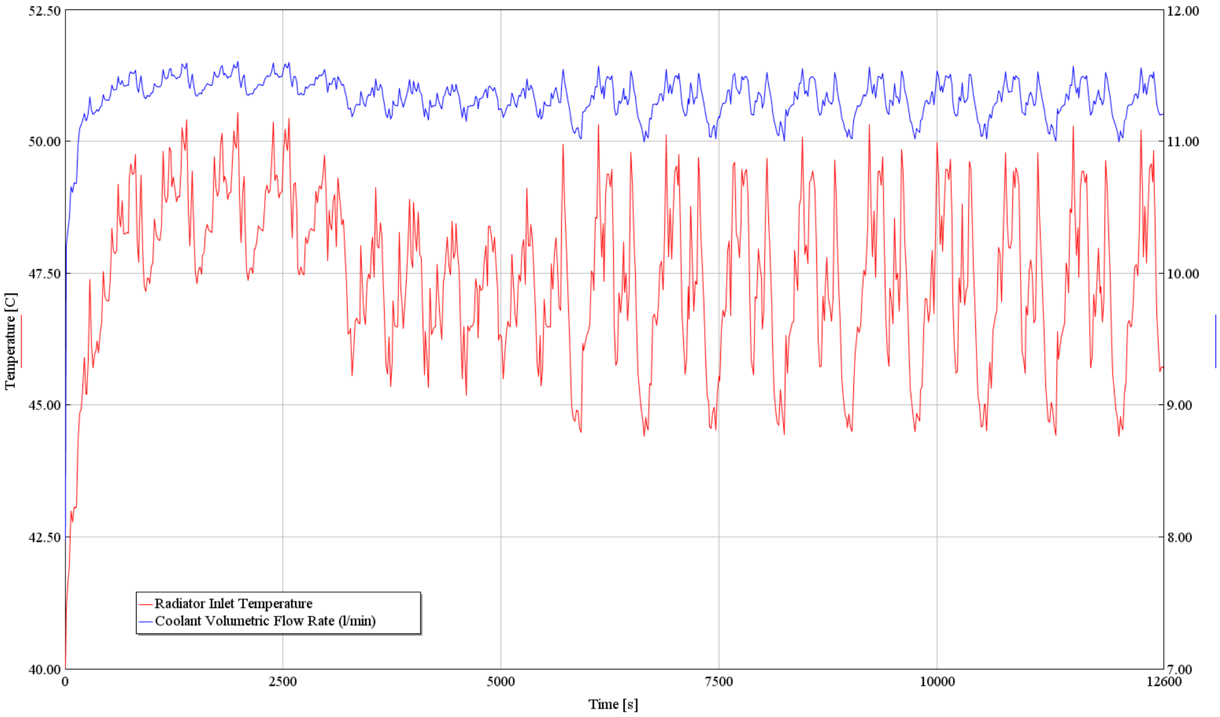

Figure 9. Coolant temperature at radiator inlet and coolant volumetric flow rate vs time

Another check, mainly required by a safely operation and lifetime preservation for motor and inverter, has been done on the temperature variation between the inlet and the outlet of those components, which are provided in Figure 10 and Figure 11. As required for the inverter preservation in WP4, it has been verified that the coolant temperature variation across this component never overcomes 2°C.

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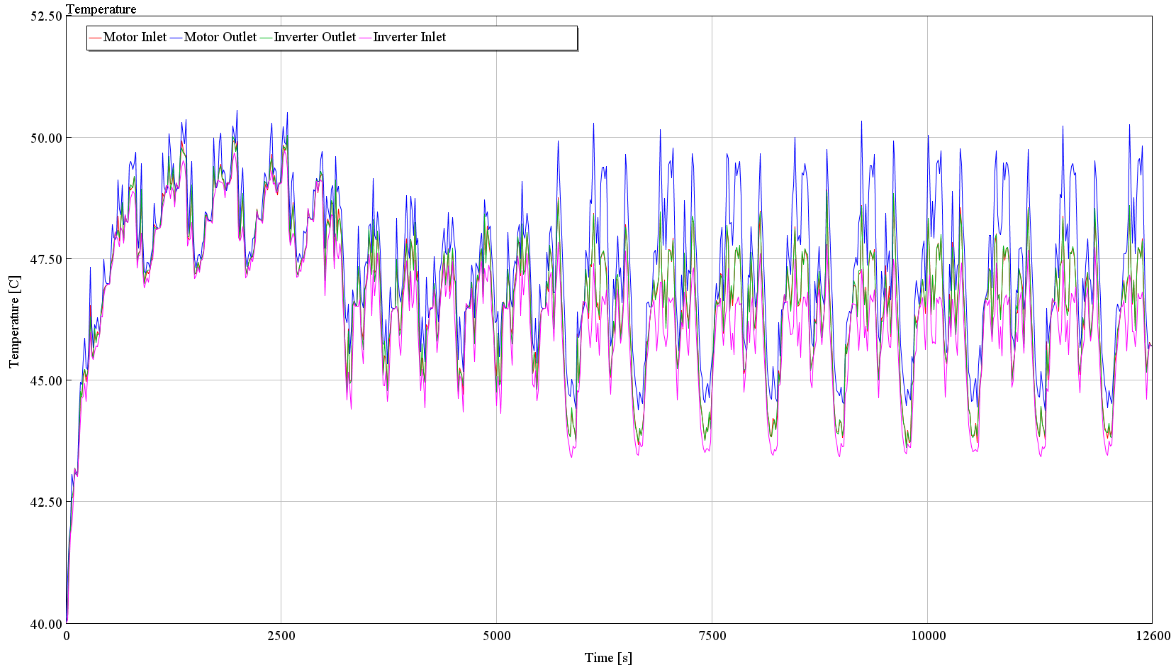

Figure 10. Motor and Inverter inlet and outlet temperature vs time

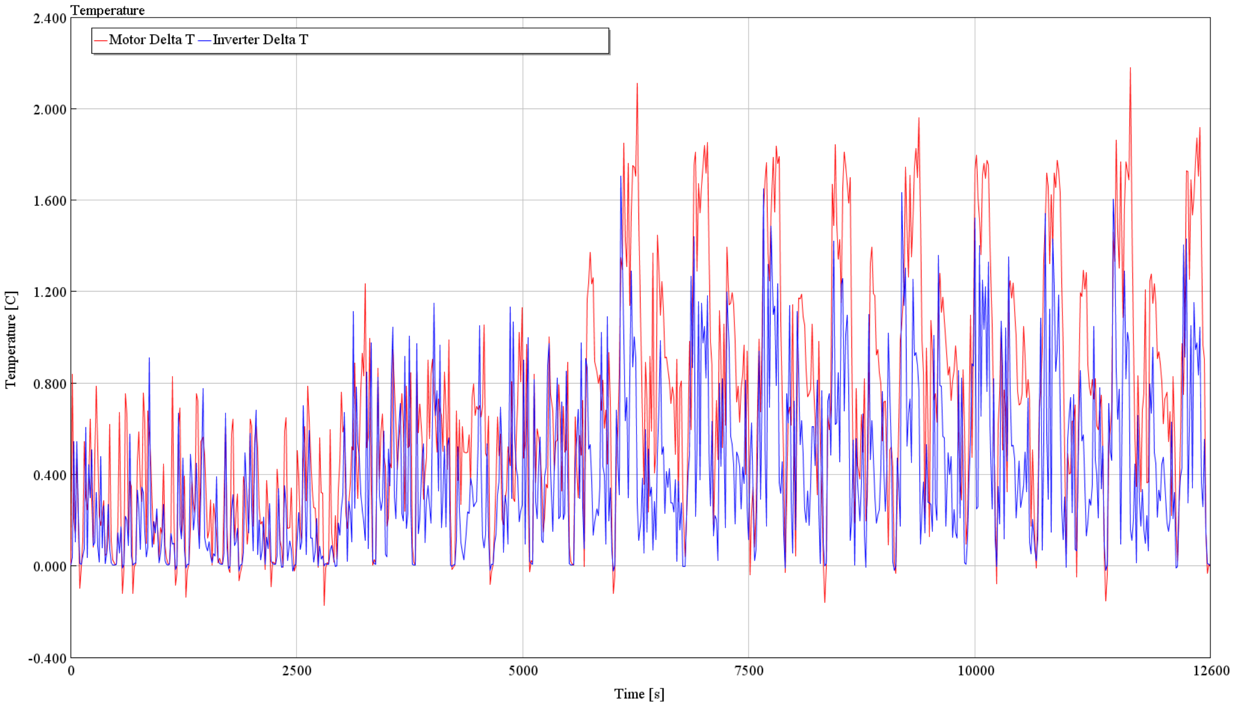

Figure 11. Temperature difference between Motor and Inverter inlet and outlet

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WLTC Scenario with altimetric variation

The same speed trace has also been simulated by considering also the road altimetric variation, shown in Figure 12.
Figure 13 and Figure 14 show the heat rejections of the motor, inverter and battery with respect to time. As one can observe in Figure 14, the heat rejections have a variability influenced also by the road slope variation and not only on the speed trace, as it was in the previous case.

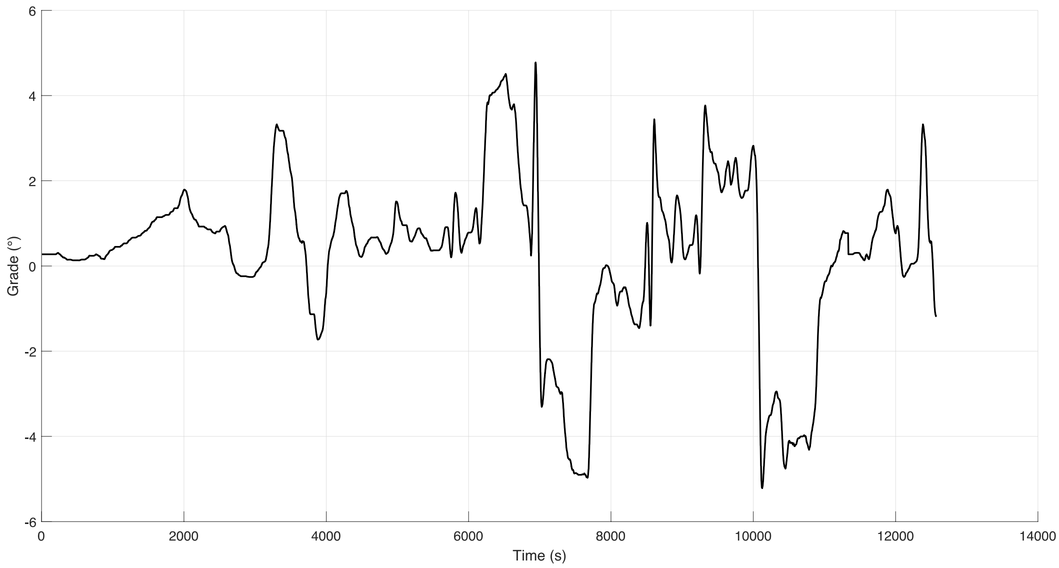

Figure 12. Altimetric variation (°) vs time

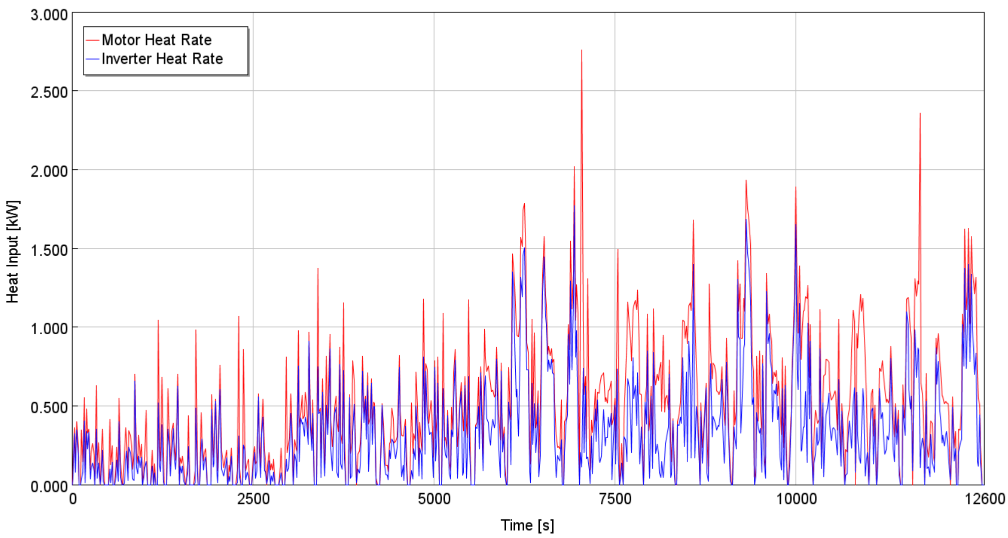

Figure 13. Motor and Inverter heat rejections vs time

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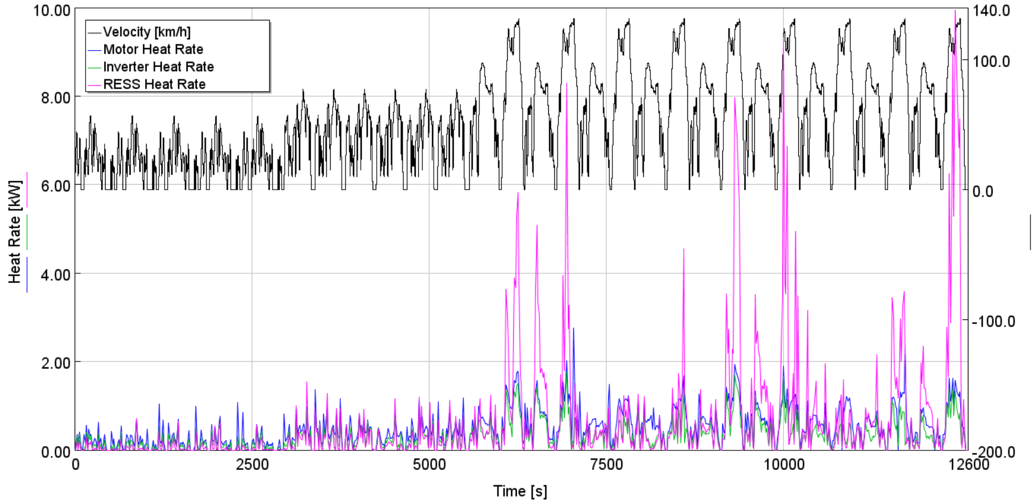

Figure 14. Motor, Inverter and battery heat rejections vs time vs speed trace

Figure 15 shows the coolant temperature at radiator inlet and the coolant volumetric flow rate through one pump with respect to time. Again, the project constrains mentioned in the Introduction are always met as the coolant temperature never overcomes 65°C while the coolant volumetric flow rate across each pump nevers goes below 10 l/min.

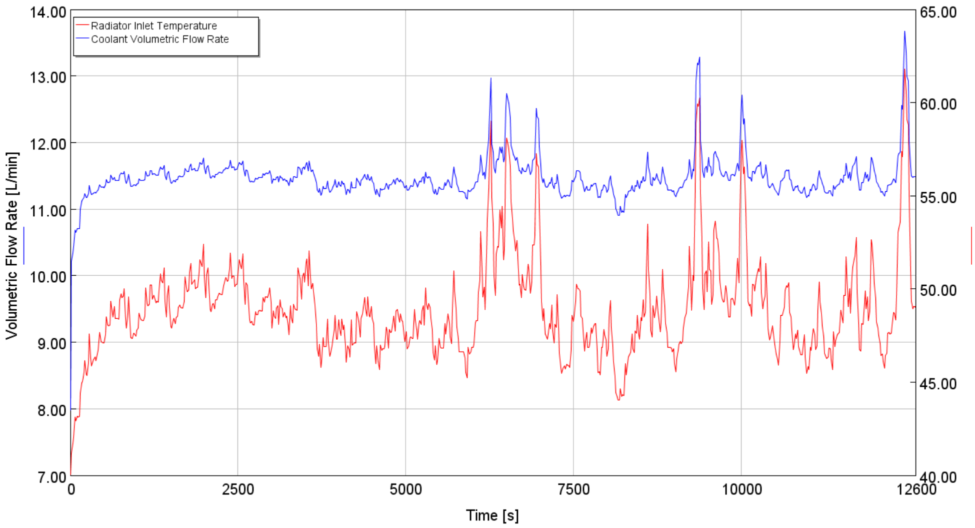

Figure 15. Coolant temperature at radiator inlet and coolant volumetric flow rate vs time

Another check, mainly required by a safely operation and lifetime preservation for motor and inverter, has been done on the temperature variation between the inlet and the outlet of those components, which are provided in Figure 16 and Figure 17. Here, the temperature variation across the inverter goas above 2°C in a few occurrences. Nonetheless, it is worth recalling that this scenario is quite demanding, since there is a significant road slope variation, with an ambient temperature of 40°C and a high vehicle weight. Moreover, this result may be affected by the assumption on the heat rejection of the battery which is not under study in the present project. For this reason, a sensitivity analysis on the effect of the battery thermal load has been carried out and is presented in the following Section.

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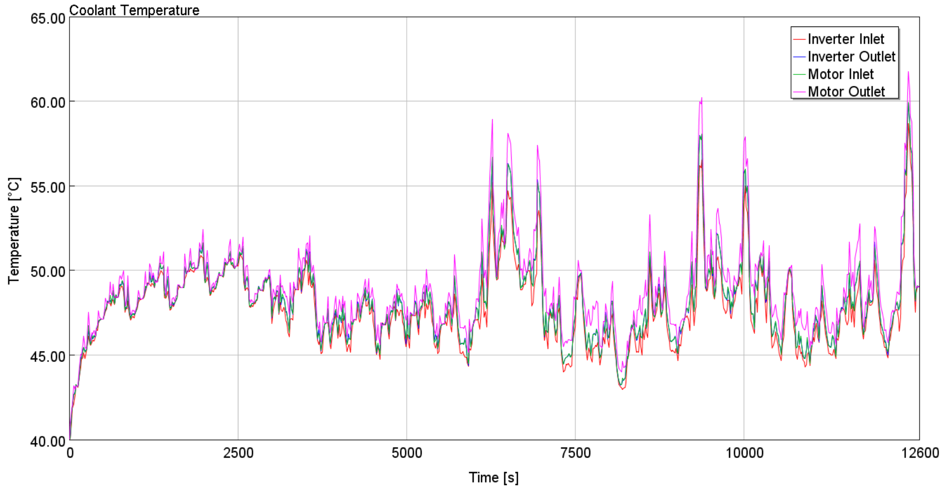

Figure 16. Motor and Inverter inlet and outlet temperature vs time

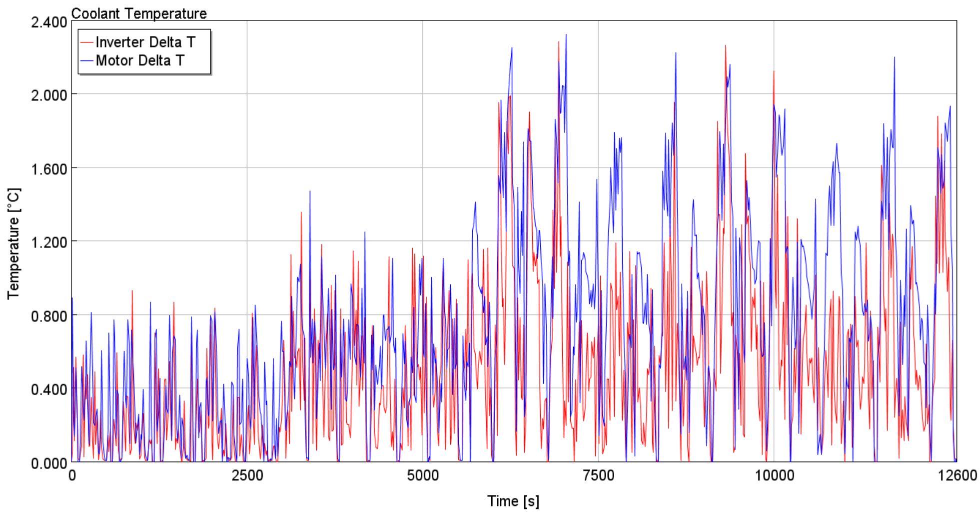

Figure 17. Temperature difference between Motor and Inverter inlet and outlet

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Sensitivity Analysis on Battery Losses

Since the battery losses cannot be retrieved from calculated or experimental data and are estimated by using a model of a likely different battery, a sensitivity analysis has been carried out on the battery thermal load. In particular, the thermal load estimated by means of Eq.(3) has been multiplied by a weighting factor varied as per the following values: 0.8, 1, 1.2.

This analysis is further justified by the final layout of the entire cooling circuit of the vehicle, which has a separate circuit for the battery cooling. As shown in Figure 1, the RESS radiator receives only a portion of the battery coolant flow rate, which implies that only a percentage (unknown) of the battery heat is rejected through this heat exchanger.

Results are provided for the scenario with no grade to avoid a superimposion of the effects on the heat rejections in Figure 18 for the coolant temperature at radiator inlet and in Figure 19 for the pump volumetric flow rate.

Multiplication factor equal to 1 coincides with the above presented results. It is immediate to note that the temperature reached at the radiator inlet is always much lower than 65°C.

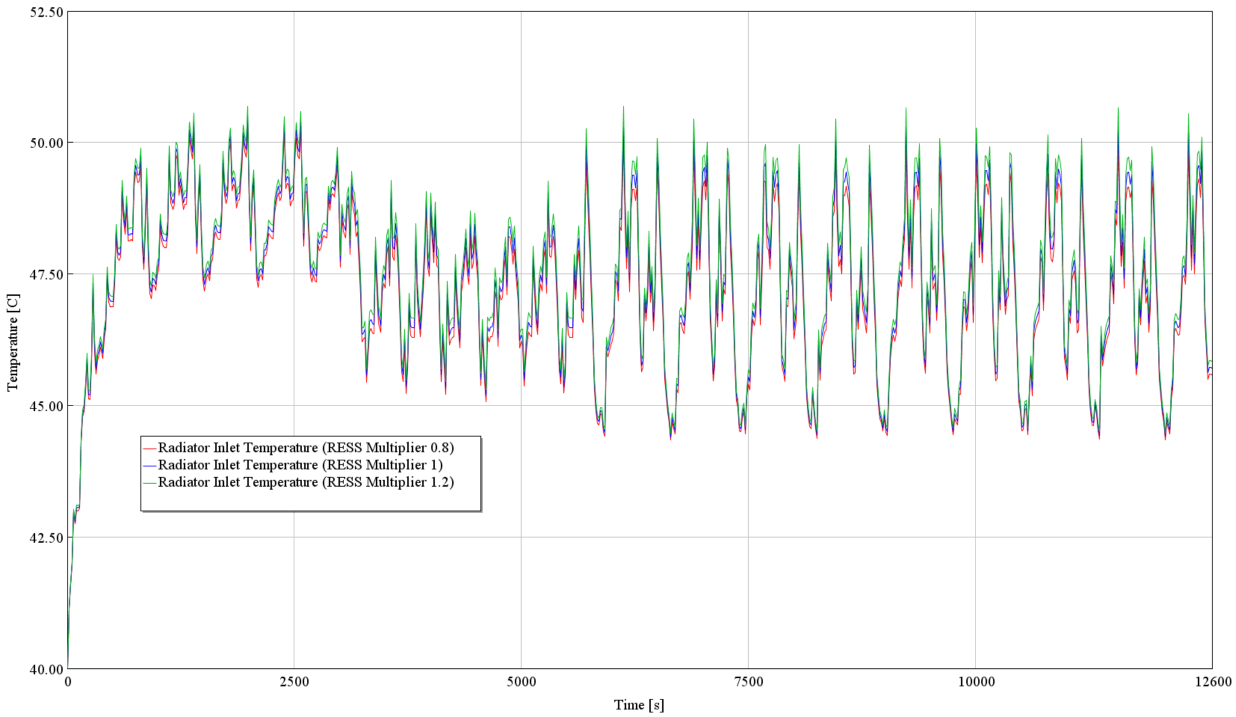

Figure 18. Coolant temperature at radiator inlet vs time

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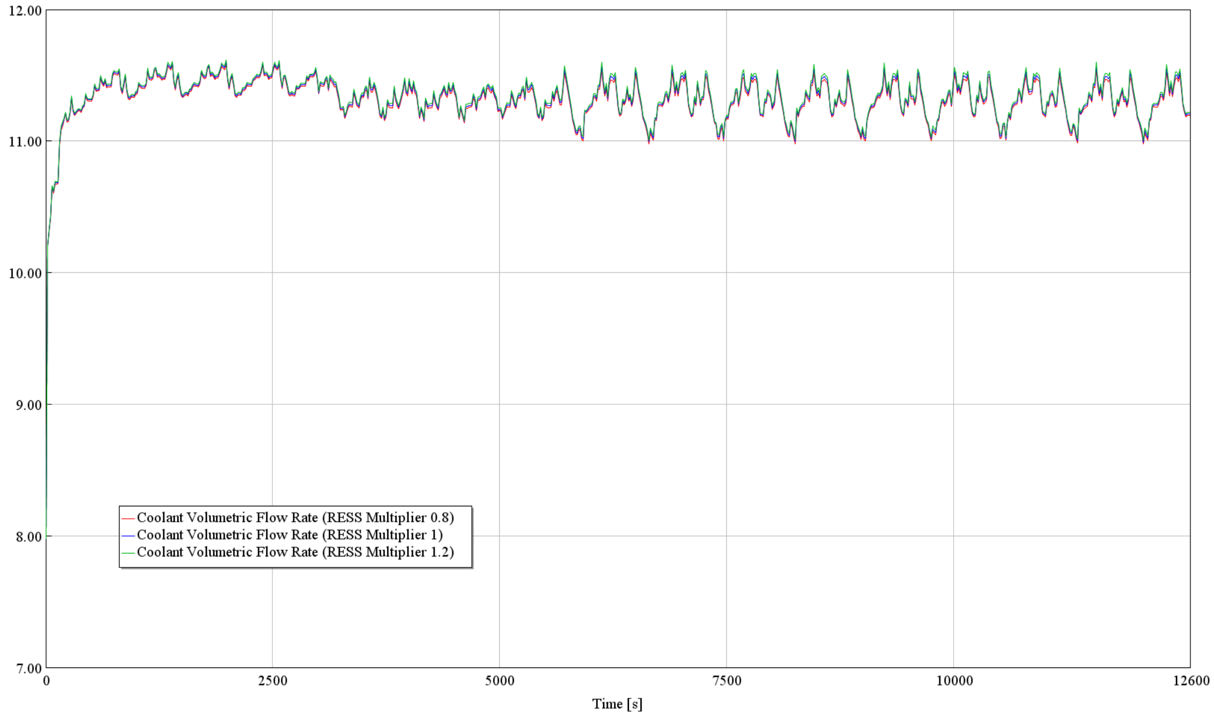

Figure 19. Pump Volumetric flow rate vs time

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Conclusions

The final output of Task 5.4 reported in the present deliverable 5.4 is a robust model of the entire system, which couples a quasi-steady simulator of the entire vehicle and a 1-D simulator of the cooling circuit, comprising of both coolant and air side. The model has been employed to verify the effectiveness of the cooling circuit control to be implemented in the demonstration vehicle. It is woth nothing that the control strategy has been inherited from the donor vehicle so to guarantee robusteness and reliability, the pump speed and fan input signal (free parameters) have been controlled so to respect constaint in every working points. Nevertheless, the design of a novel control strategy is still under investigation and any potential result will be spread among the partners as further extension of the work done. It is hoped that this investigation leads to interesting results, which may be published on a scientific paper.

With the respect to the present analysis - which builds upon the past Tasks and Deliverables and concludes the work done within Work Package 5 on the Cooling Circuit – results reported in the present Deliverable 5.4 demonstrate that the cooling circuit, in its present configuration and with the implemented control strategy, is able to fulfil the constraints on the minimum coolant flow rate (10 l/min) and on the maximum coolant temperature (65°C), even in high demanding scenarios, such as high speed, high grade and 40°C of ambient temperature and over a real-like driving cycle, i.e. WLTC.

With respect to scientific publications, one abstract has been submitted to an international conference which will be held in Italy in June 2020 and is under review. Moreover, an international paper focused on pertinent topic and titled (Performance Evaluation of an Electric Vehicle with Multiple Electric Machines for Increased Overall Drive Train Efficiency, https://doi.org/10.4271/2019-24-0247) has been successfully published by SAE International.

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Appendix

List of abbreviations

AC	Air Conditioning
EM	Electric Motor
GT	Gamma Technologies
HVAC	Heat Ventilation And Air Conditioning
IDM	Integrated Drive Module
INV	Inverter
OBC	On-Board Charger
RESS	Rechargable Energy Storage Source (Battery)
WP	Work Package

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2. D5.3 System modelling for the evaluation of the final design, related Task 5.3 of WP5, submitted on August 2019. Laura Tribioli, SCIRE
3. Gamma Technologies official website. URL http://www.gtisoft.com.
4. D5.2 Thorough data collection from other partners and WPs and further analysis to build up a database, related Task 5.2 of WP5, submitted on July 2019. Laura Tribioli, SCIRE
5. D2.1 Preliminary design of modular drivetrain system, related Task 2.1 of WP2, submitted on April 2018. Nimananda Sharma and Yujing Liu, Chalmers University of Technology
6. D2.2 System specification of prototype, related Task 2.2 of WP2, submitted on November 2018. Deepak Singh, NEVS

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