DRIVEMODE

Integrated Modular Distributed Drivetrain for Electric & Hybrid Vehicles

Document title: D5.1 Documentation of the basic concept of the cooling circuit

D5.1: Documentation of the basic concept of the cooling circuit
WP 5, T 5.1
Authors: Laura Tribioli (SCIRE)

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DRIVEMODE

Technical references

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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)

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Executive Summary

An overview of the deliverable objectives, link to relevant tasks and to the fulfilment of objectives. In case of deviations (content, time) please provide a full justification and an assessment of impacts to linked tasks and to overall project implementation.

The purpose of the deliverable is to provide information about the basic design of the cooling circuit and the preliminary evaluations carried out in order to identify the basic layout will be presented.
This deliverable is linked to Task 5.1 Development of cooling circuit concept, which is aimed at addressing the development of the basic concept of the vehicle cooling circuit on the basis of the vehicle platform provided by NEVS. The baseline vehicle platform includes cooling circuit components and functionalities to which the new IDMs must be adapted.
The work carried out within this Task dealt with a preliminary analysis of the cooling system, aimed at the sizing of the coolant pump. The work has been divided into four main steps:

1. Data gathering from NEVS on the existing cooling circuit from the baseline vehicle; understanding of constraints;
2. Evaluation of need/possibility of improvements and modifications for the cooling circuit of the demo vehicle;
3. Data gathering from SEMIKRON and AVL for a rough estimation of the pressure drops and thermal loads of the components of the IDM;
4. Proposal of different solutions for the cooling circuit.

All partners of this work package contributed to it by providing information useful for the definition of the basic layout, connections and requirements of the cooling of the specific component.

Attainment of the objectives and if applicable, explanation of deviations

The deliverable reports the decision made about the basic design of the cooling circuit. One possible final layout has been identified as a trade-off between different solutions, attaining the objective of the deliverable itself, perfectly in time. Nonetheless, refinements will be carried out at the end of the second Task (Task 5.2 Data collection from other WPs) as soon as more reliable data will be gathered from the other partners, while the final cooling circuit design definition and sizing will be the objective of Task 5.3 Cooling circuit layout definition and sizing.

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1. Introduction

The aim of this work package (WP5) is to design and evaluate the cooling circuit performance of the integrated vehicle system. One of the goals of this WP is to use the minimum number of cooling elements, in order to design a single cooling circuit for all devices.

Task 5.1 Development of cooling circuit concept addressed the development of the basic concept of the vehicle cooling circuit on the basis of the vehicle platform provided by NEVS. Since the existing vehicle platform already includes cooling circuit components and functionalities, the new IDM must be adapted to them, since guaranteeing interfacing with other car systems is one of the project technical objectives.

Therefore, moderate changes in the existing system are possible, if needed for the sake of modularity, easiness of integration and reduction of overall costs, but in this case state-of-the-art components should be selected to ensure cost-effectiveness of the overall system.

The requirements for the IDM have been identified in D2.1 Preliminary design of modular drivetrain system, related Task 2.1 of WP2, which has been submitted on April 2018. Therefore, requirements are known and fixed. Since, the IDM will be used as a module, four different layouts have been defined to attain different powertrains for different vehicle classes, which vary in terms of total torque and total power output (i.e. vehicle class requirements), while scalability of the IDM itself is not considered. For the demonstration vehicle F2 layout has been selected and the following analyses will consider only this configuration.

The specifications of the demo vehicle have been identified in D2.2 System specification of prototype, related Task 2.2 of WP2, which has been submitted on November 2018. The objective of this Task was the definition of performance requirements of subsystems including the cooling system, and to define interfaces among the subsystems being developed based on prevalent automotive industrial standards.

The starting point for this Task is therefore the existing cooling system, which will be presented in Section Background.

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2. Background

The schematic diagram of the existing propulsion cooling system is shown in Figure 1.

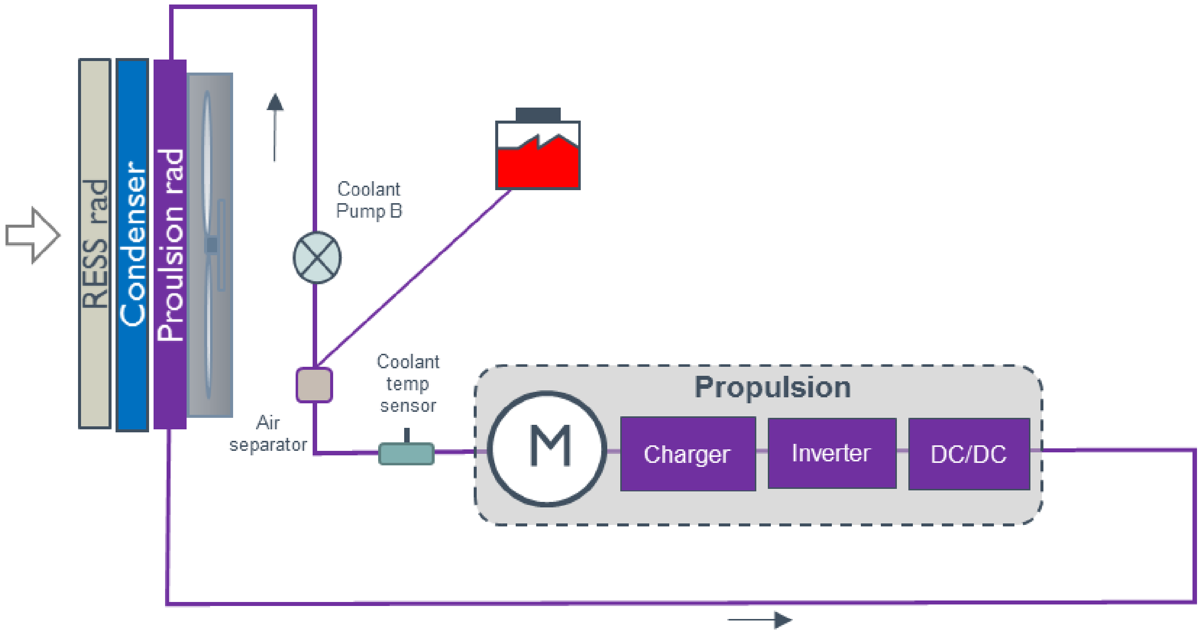

Figure 1. Schematic of propulsion cooling circuit

Main components of the circuit are:

- Coolant: to cool down the propulsion components the coolant is circulated around the coolant system by the pump. The coolant consists of water mixed with ethylene glycol, basically 50% water + 50% glycol. The addition of glycol is needed to reduce freezing point temperature, improve corrosion resistance and raise up the boiling point temperature.
- Pipes and hoses: used to connect different parts of the coolant circuit and to transfer the coolant mixture between these parts. Pipes and hoses inner diameter is of 19 mm, locally 18 mm in Quick Connectors.
- The pump: used to force the coolant to circulate through all the components. The existing pump is an electric pump whose operation characteristics are shown in Figure 2.
- The coolant tank: used in the existing vehicle as accumulator and surge tank, it has a volume of 1.5 liter, while coolant fluid volume is 1.1 liter. Extra volume of tank is needed to accommodate for fluid volume expansion.

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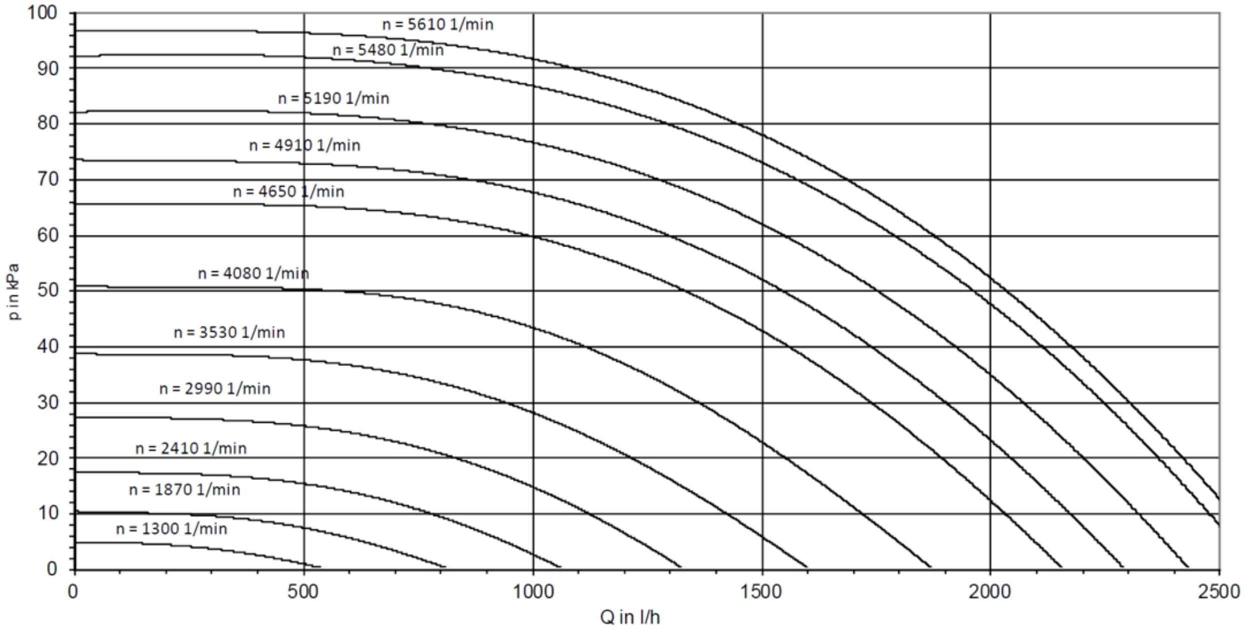

- The electric fan: used to suck air in and increase the air through both the propulsion radiator, condenser and RESS radiator
- The propulsion radiator: used to cool down the coolant which passes through the propulsion components. The existing radiator is quite oversized as it is derived from a conventional internal combustion engine powered vehicle.
- The condenser: heat exchanger used for AC circuit. The coolant flowing through this heat exchanger is different from the coolant of the propulsion loop, but fan serves also this component.
- The RESS radiator: heat exchanger used for the battery cooling circuit. The coolant flowing through this heat exchanger is different from the coolant of the propulsion loop, but fan serves also this component.

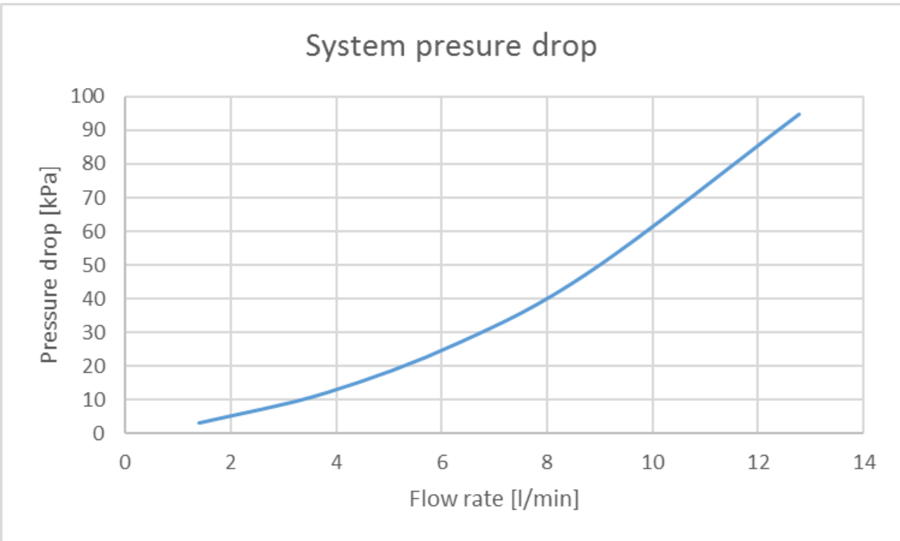

Figure 3: Pressure Drop vs Flow Rate of entire cooling loop.

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Simulated trend of pressure drops against coolant volumetric flow rate of the overall cooling loop in the existing vehicle shown in Figure 3 and those of each component of the cooling loop are shown in Figure 4.

The simulation has been carried out by NEVS under the following assumptions:

- Pump is running on five different speeds, covering the entire range
- Constant coolant temperature at 23^{O}C Coolant temperature kept constant at 23°C

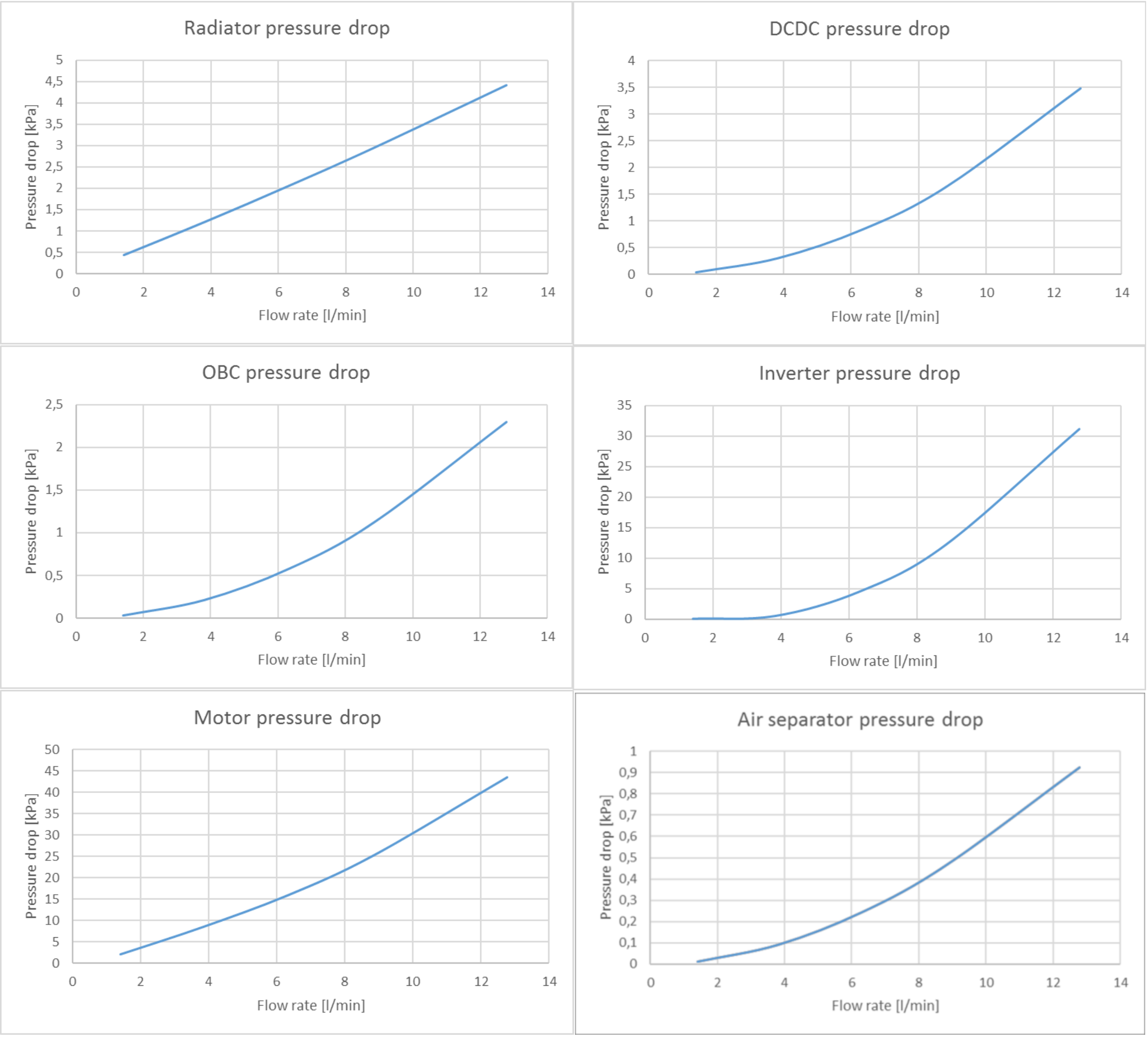

Figure 4: Pressure Drop vs Flow Rate at individual components of cooling loop.

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3. Preliminary Analysis

Data available from the existing vehicle and presented in the previous section have been integrated with preliminary data available from the components. Basically, these data are assumptions which have yet to be verified both with simulations and experimental measurements.
Data provided by the partners are summarized in Table 1:

Table 1. Preliminary requirements for the cooling circuit

e-Motor	
T (inlet)	< 65°C
Pressure Drop	< 500 mbar (to be verified) @ 10 l/min
Vol. flow rate	> 10 l/min @ maximum power
Inverter	
T (inlet)	< 65°C (TBD)
Pressure Drop	130 mbar or 300 mbar @ 10 l/min
Vol. flow rate	> 10 l/min (TBD) @ maximum power

The constraint on the minimum volumetric flow rate imposes to use two pumps, one for each module. This has been found coherent with the modularity requirement of the overall project, since each module comes with its own pump.

In addition to this, oil cooling has been proposed as a solution to improve the e-motor cooling and thus increase the component's performance, in particular the power density can be increased up to 4kW/kg with oil cooling of windings, even if there is almost no effect if oil is used for the jacket. Additional reason for investigating this solution is the evaluation of possibility of using in the loop the gearbox lubricating oil, as coolant medium, to increase the level of modularity. On the other hand, oil cooling has been considered not beneficial for the inverter. Moreover, the use of oil cooling for e-motor will require an additional heat exchanger and of an oil pump to be sized and designed in order to cool down the oil itself and to guarantee the proper functioning of the component.

Starting from the basic layout presented so far, three alternatives for the cooling circuit have thus been proposed:

1. Layout n.1: Cooling with EGL mixture
2. Layout n.2: Cooling with OIL
3. Layout n.3: Cooling with OIL and EGL mixture

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Layout n.1: Cooling with EGL mixture

The schematic of this first layout is provided in Figure 5. This is the simplest layout as only one coolant type (i.e. EGL) circulates in the overall circuit. This layout is compact, since motor and inverter can be cooled in series by the same coolant flow and a minimum number of components is required.

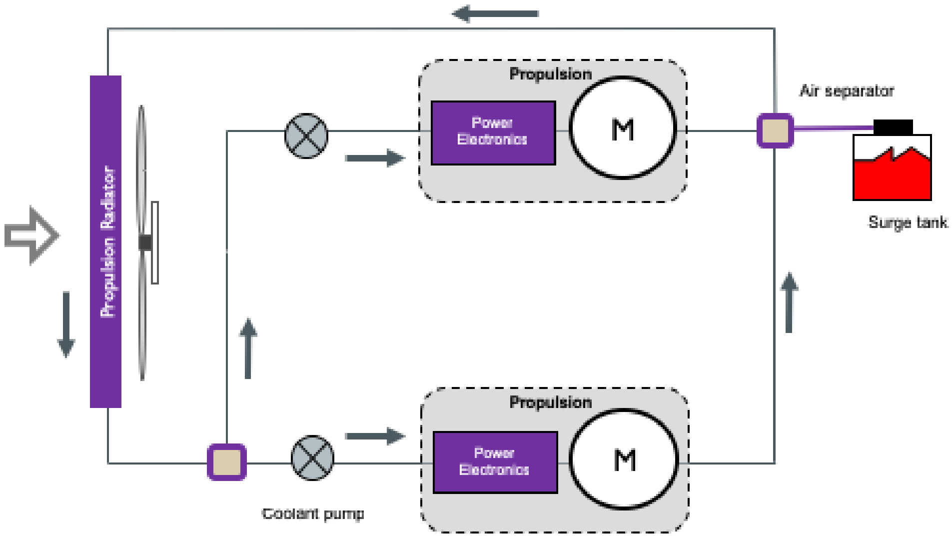

Figure 5. Schematic of cooling with EGL

Layout n.2: Cooling with OIL

The schematic of this second layout is provided in Figure 6. This layout uses oil for components cooling and needs EGL for the cooling of the oil, since the propulsion radiator cannot be used to cool it down. This layout may guarantee higher power density for the e-motor, but decreases inverter performance and requires two more components, namely the oil cooler and the oil pump. On the other hand, only one pump is required for the EGL, in contrast with the first layout.

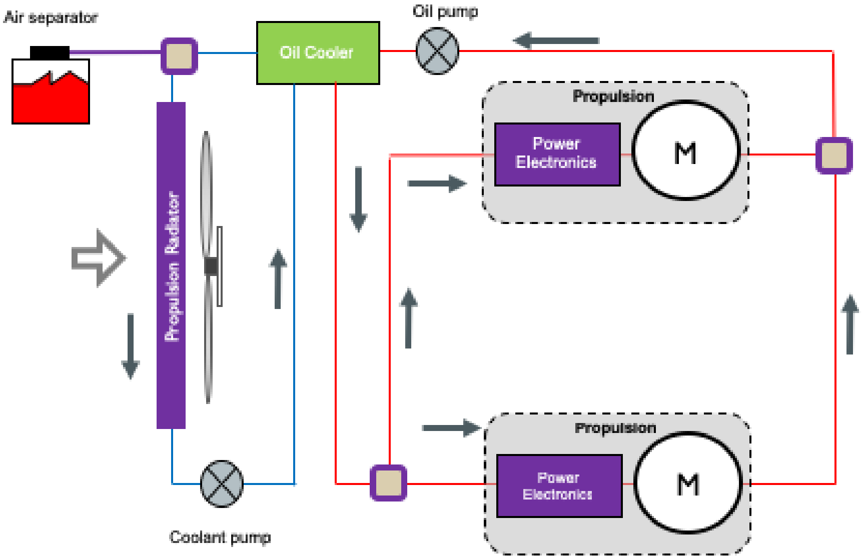

Figure 6. Schematic of cooling with OIL

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Layout n.3: Cooling with OIL and EGL mixture

The schematic of this third layout is provided in Figure 7. This layout uses oil for the e-motor cooling and uses EGL both for the cooling of the oil and the cooling of the inverter. Since the circuit is split into two sub-circuits, one for the e-motor and one for the inverter, this layout is the one that allows for the highest level of optimization among all the alternatives proposed, in terms of individual component performance, but still requires two more components, namely the oil cooler and the oil pump.

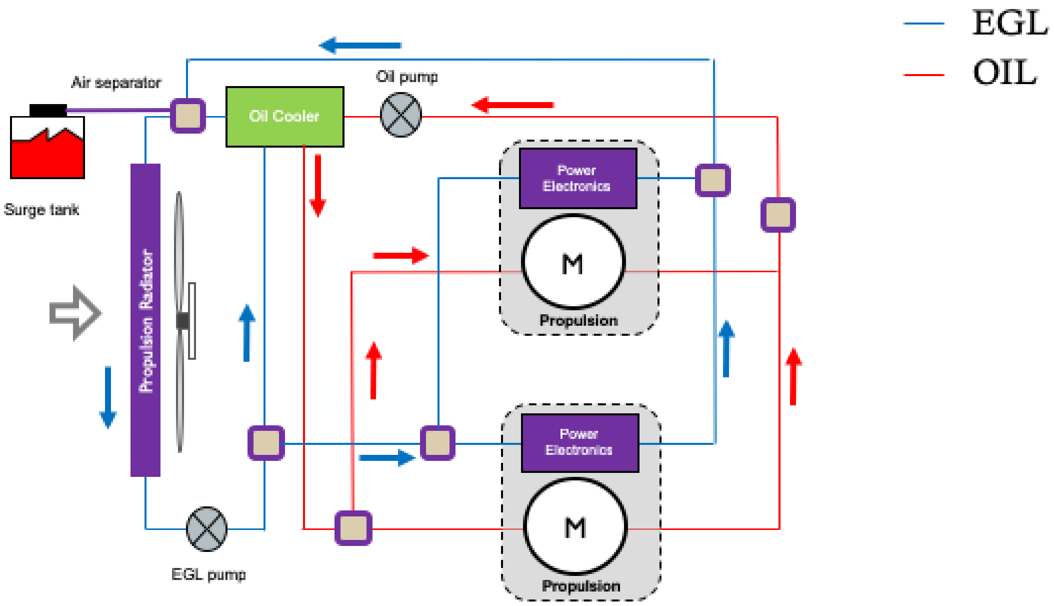

Figure 7. Schematic of cooling with OIL and EGL

A SWOT analysis for the use of oil or EGL as cooling medium is proposed in Figure 8. Briefly, the most important opportunities of using oil are: increased power density for e-motor and optimization of both design and strategy of the cooling circuit, in spite of additional components which affect space and costs and worsening of inverter performance.

On the other hand, if EGL is used, design is faster, cost-effective, less space-consuming, and interfacing with other car systems - which is another project technical objective of the project - is ensured. Moreover, the use in the electric and the electronic components of the same oil that passes through the gearbox is not recommended since slivers from the gearbox may damage the e-motor and/or the inverter.

Therefore, the layout selected for the cooling circuit is the first one.

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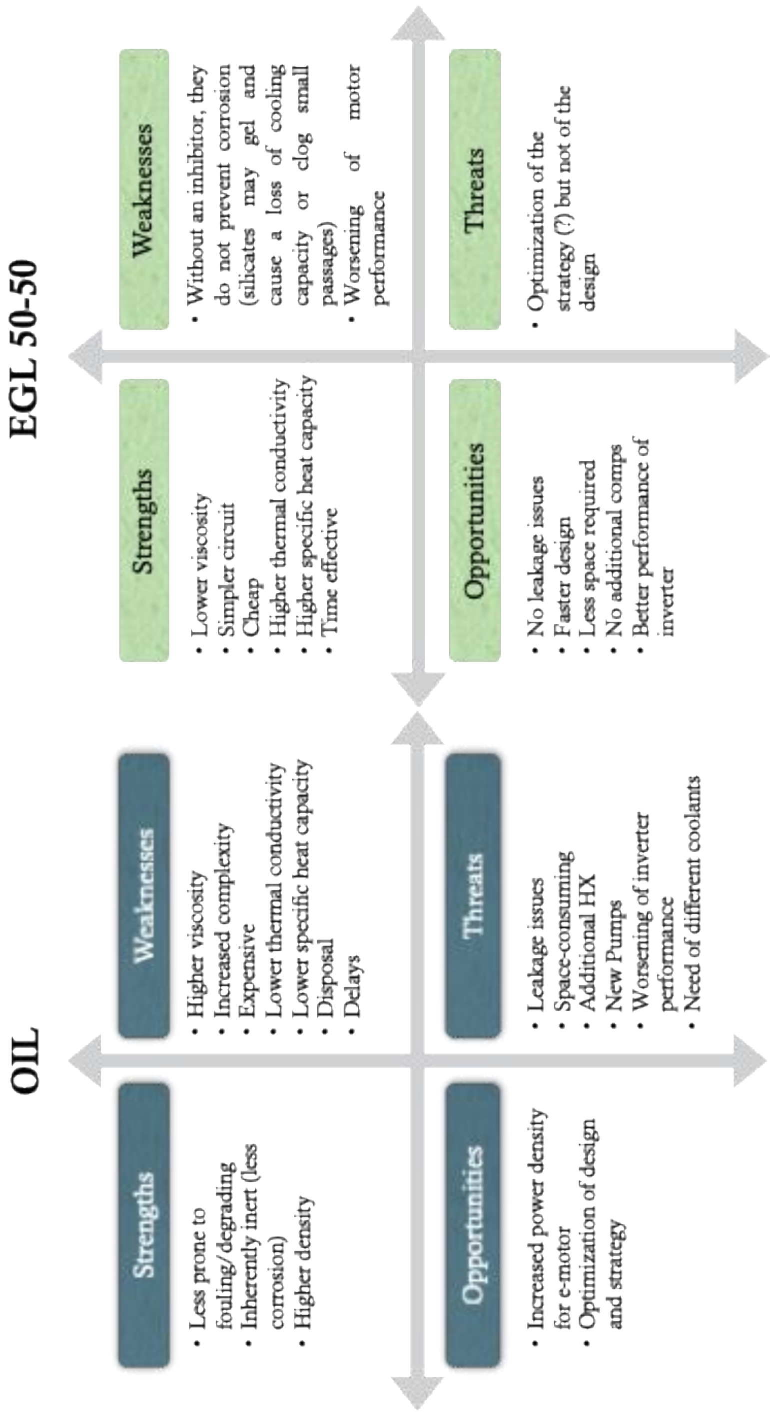

Figure 8. SWOT analysis of oil vs EGL

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4. Basic Concept Design

Basic specifications regarding cooling of the propulsion system in the demonstration vehicle can thus be summarized in the following list:

- Cooling method for the inverter: Direct liquid cooling of the pin fin module
- Cooling method for the e-motor: Trapezoidal channels on the stator housing
- Coolant used: 50% water + 50% glycol
- Max Coolant temperature: 65 ^{O}C
- Min Flow rate@ maximum power: 10 l/min for each IDM
- Number of pumps: one for each IDM

A complete schematic of the circuit is provided in Figure 9, while the overall circuit three-dimensional drawing is shown in Figure 10.

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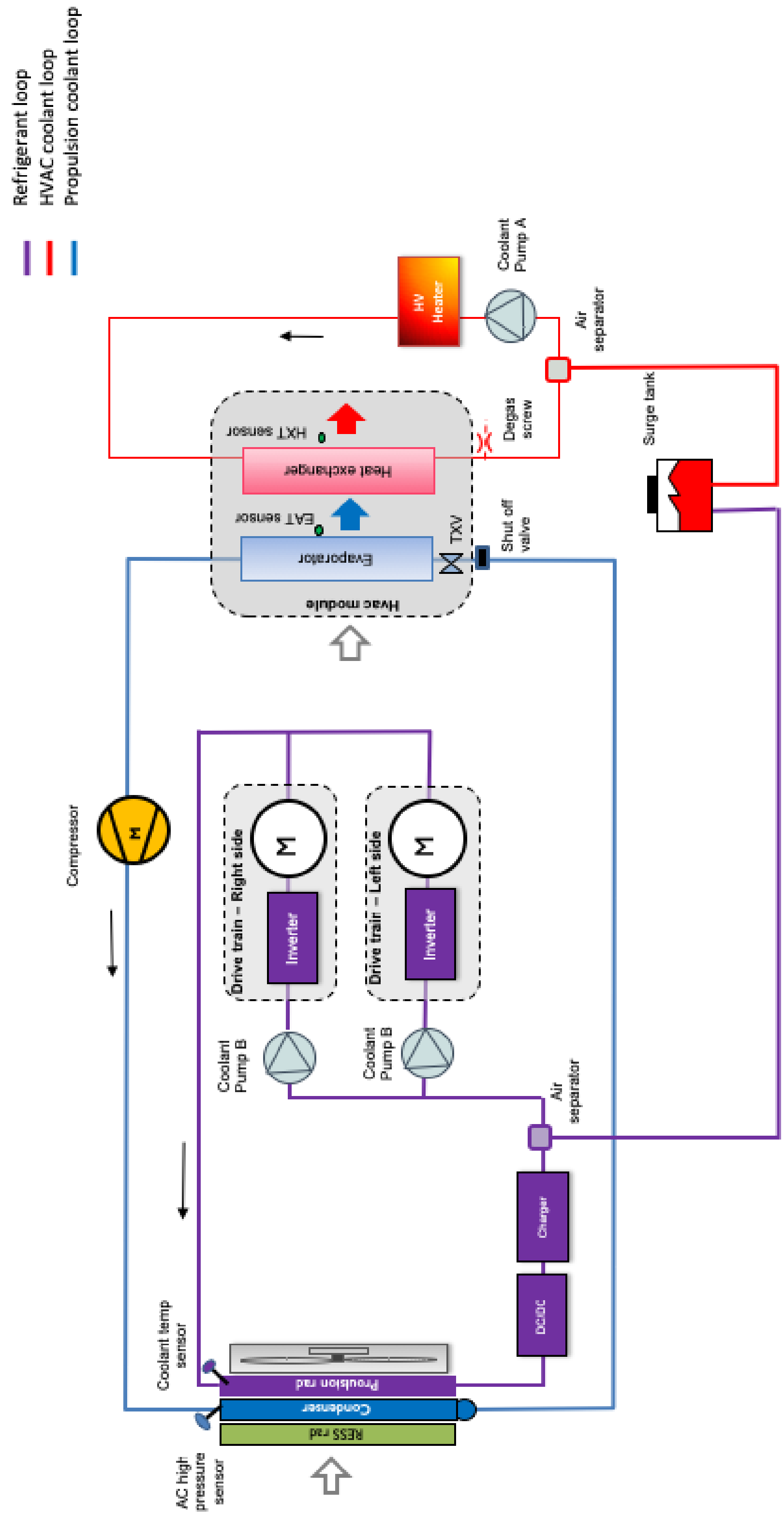

Figure 9. Final schematic of propulsion cooling circuit

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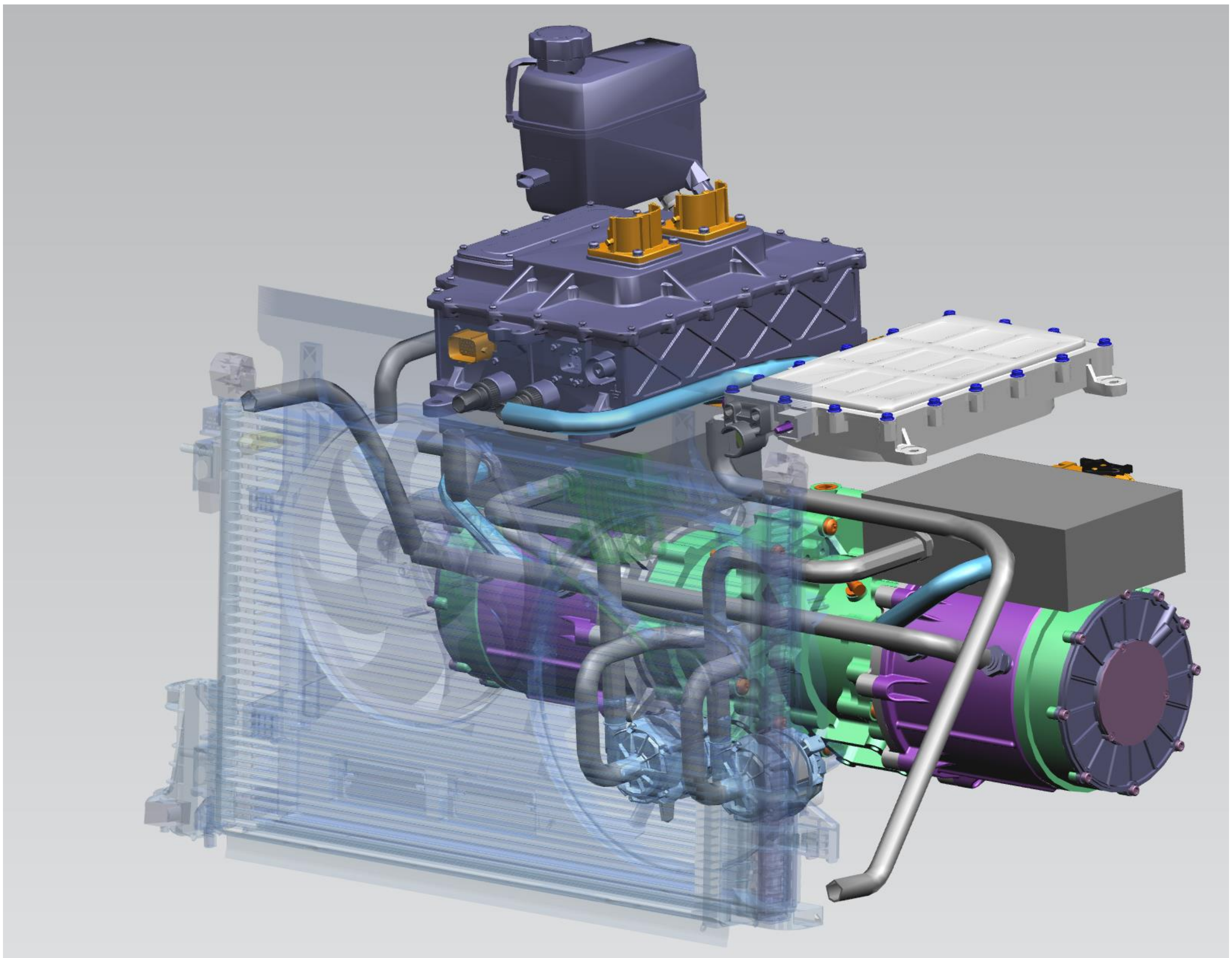

Figure 10. Overall cooling circuit drawing

On this final layout some sensitivity analyses have been performed on the overall circuit pressure drops to check if the capability of the existing pump is suitable for the circuit. The sensitivity analyses have been performed by using data of the existing components within the first proposed layout. Both the effect of pipes and hoses diameters and OBC and DC/DC location in the circuit have been investigated.

Sensitivity analysis on hoses inner diameter

A design study on the inner diameter for the cooling hoses in the common branches of the propulsion circuit has been performed. All the components data are the ones of the NEVS 93 EV project.

With reference to Figure 11, parts under investigation are those belonging to the branch in red, whose common diameter has been varied with a 1-mm increment.

The parallel hoses diameters (shown in yellow) have been kept constant, equal to 19 mm.

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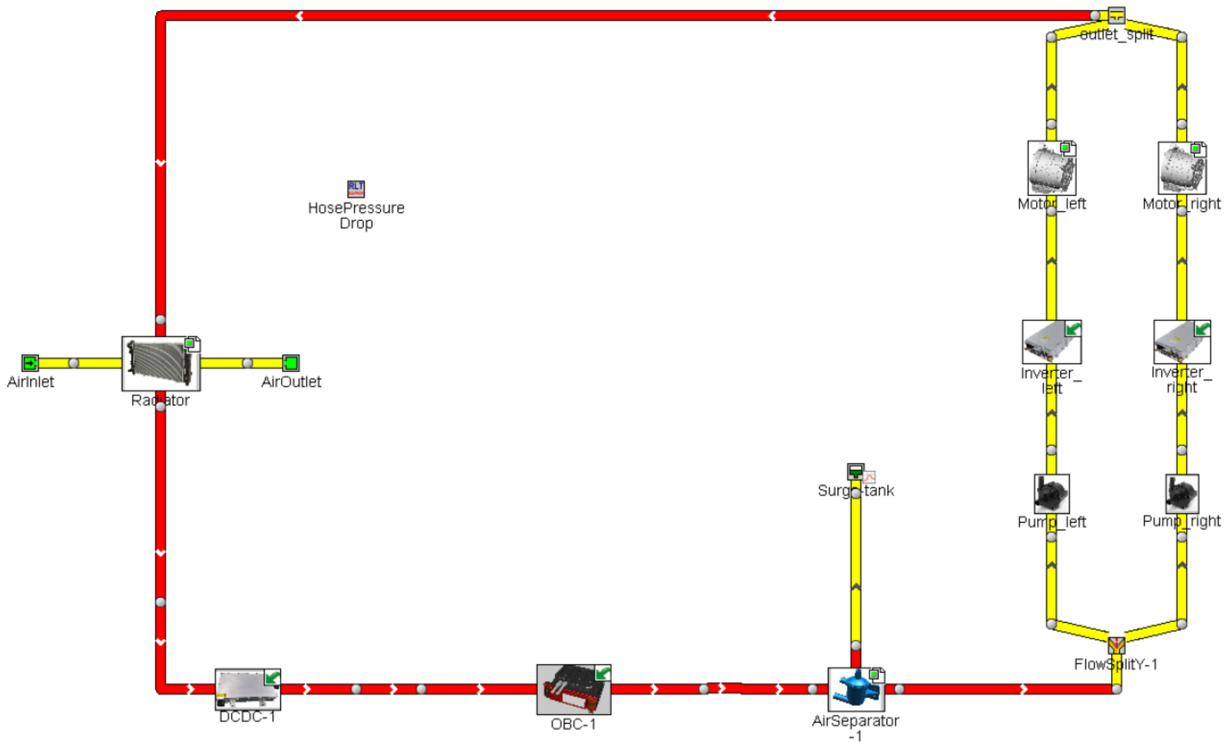

Figure 11. Propulsion circuit model in GT-Suite

Two cases have been simulated:

1. Constant speed of the pumps, equal to the maximum (5610 rpm)
2. Constant flow rate through the pumps (9.5 l/min)

Case 1: Results

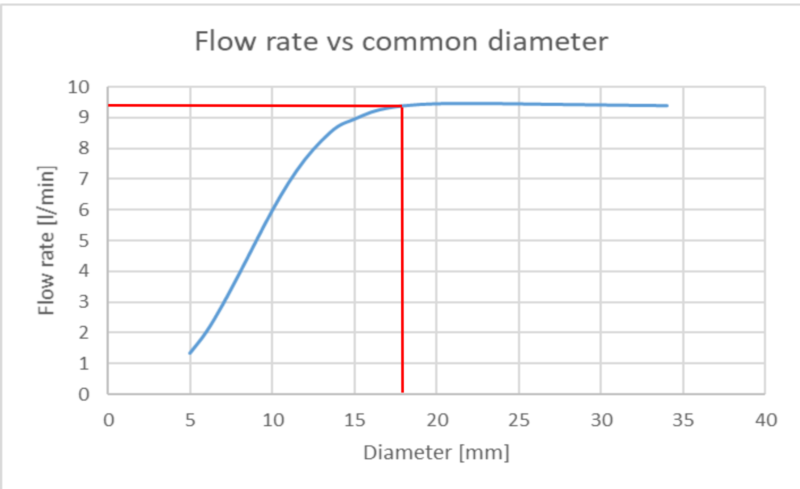

Figure 12. Flow rate vs diameter of hoses of common branch

In Figure 12 the volumetric flow rate through the motors is provided. As it is possible to note, having a diameter larger than 17 mm does not improve the flow rate noticeably and the maximum flow rate

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that can be reached is ~9.5 l/min. This implies that the hoses diameters in the common branches can be reduced to 17 mm without any notable effect on the volumetric flow rate.

Case 2: Results

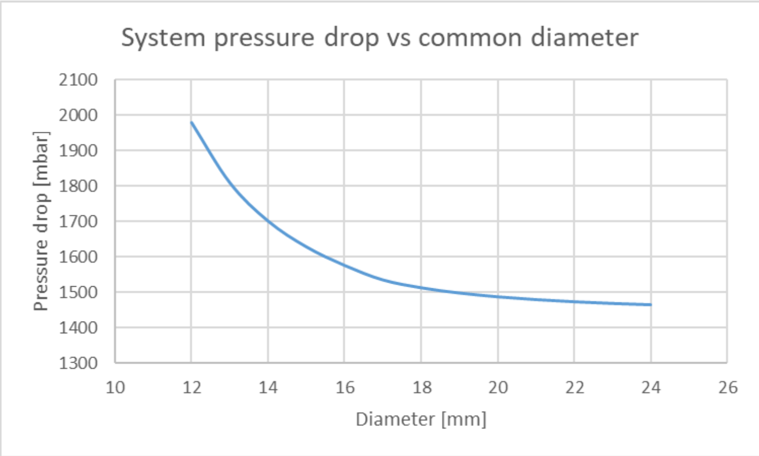

Figure 13. Pressure drops vs diameter of hoses of common branch

In Figure 13 the overall circuit pressure drops are provided against a variation of the inner diameter of the hoses in the common branch. These are the pressure drops obtained for an imposed flow rate of 9.5 l/min for each pump, which is achieved with a diameter slightly lower than 17 mm, as one may expect, only due to convergence reasons (i.e. tolerance of the solver). As one can note, again, the pressure drops do not decrease significantly as the diameter increases, therefore increasing the diameter of the hoses is not beneficial to fit the pump capacity.

Table 2. Pressure drops vs flow rate

Pressure drop [mbar] → Flow rate [l/min] ↓	**Hoses**	**Inverter**	**Motor**	**Radiator**	**Total**
10	179.8	263.5	311.6	78.0	832.9
12	242.2	364.7	406.7	96.4	1110.0
15	356.5	547.7	577.6	125.7	1607.5

Since the preliminary constraint on the minimum flow rate has been set to 10 l/min, other simulations have been performed to evaluate the pressure drops at 10 l/min, 12 l/min and 15 l/min and results are provided in Table 2. The column "Total" (i.e. the last one) represents the sum of the pressure drops given in the other columns, which does not correspond to the total pressure drops of the system. Hoses in these simulations have a 19-mm diameter.

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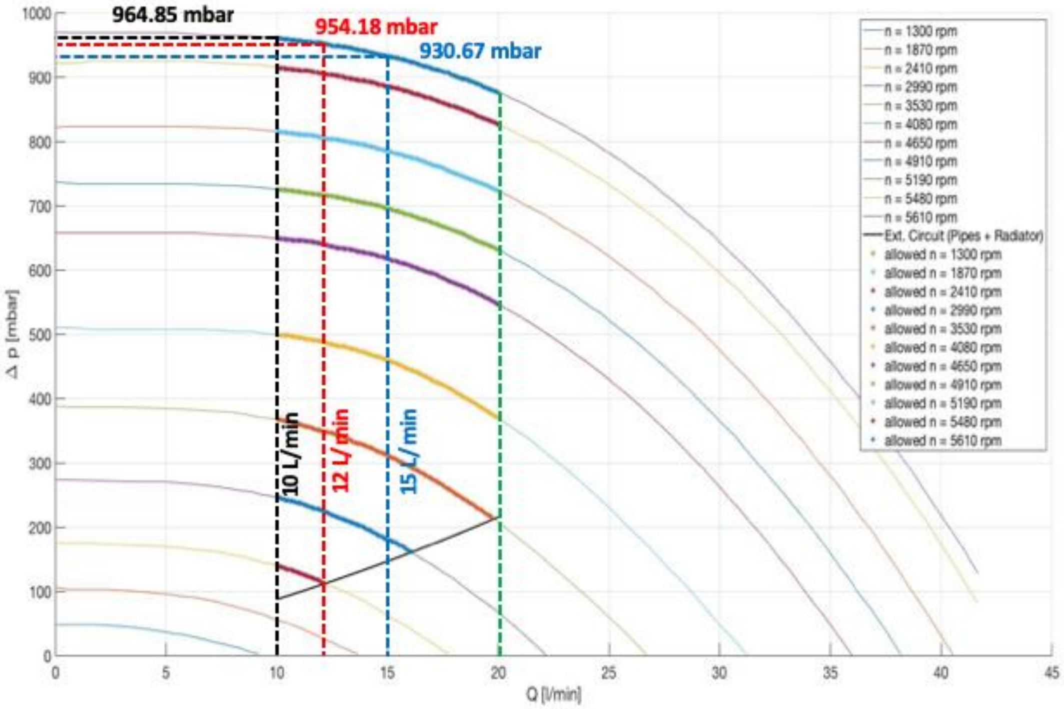

Figure 14. Maximum pressure rise @ analyzed volumetric flow rates with the existing pump

From Figure 14 it is possible to note that the existing pump is not able to meet this constraint. Running the system with NEVS 93 EV components gives a maximum flow rate of ~9.5 l/min, which does not fulfil the requirements, with a reduction of ~2.5 l/min compared to the NEVS 93 EV circuit.

Sensitivity analysis on propulsion cooling circuit layout

In order to further understand if the existing pump can be used in the demonstration vehicle, so as to avoid time and resources-related delays, another sensitivity analysis has been carried out by varying the location of the on-board charger and DC/DC converters, within the Layout n.1 of the cooling circuit, which is kept frozen corresponding to the one shown in Figure 9.

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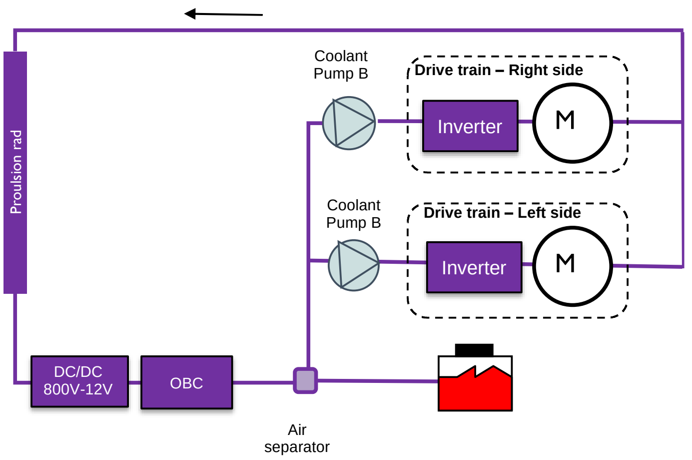
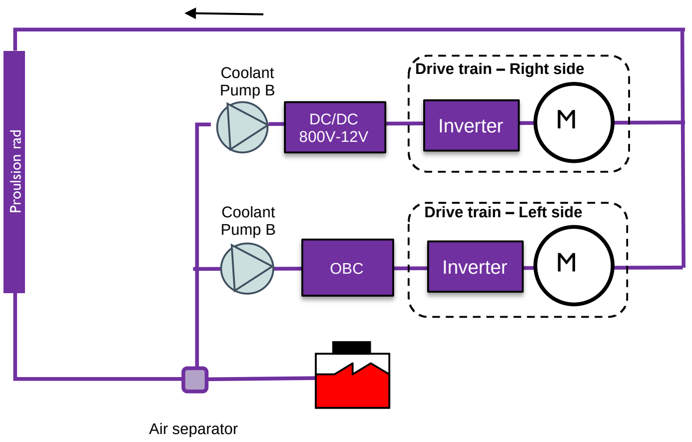
Layout n. 1

Version 1 (Baseline)



Layout n. 1

Version 2



Layout n. 1

Version 3

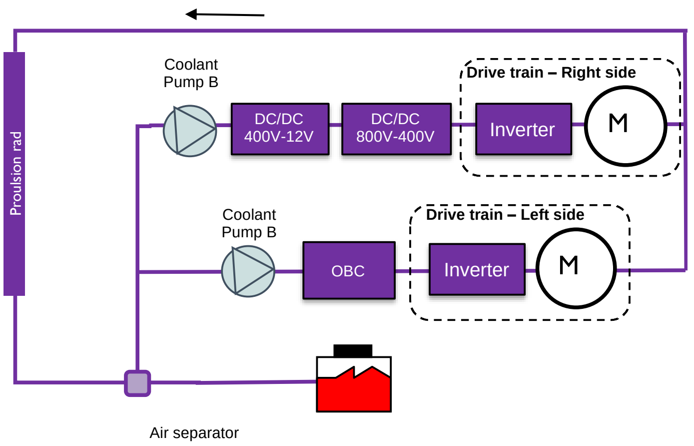


Figure 15. Different versions of the selected Layout n.1

Simulations have been performed with the pump at the maximum speed and a coolant initial temperature of 20°C. Results are provided in Table 3.

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Table 3. Flow rates at maximum speed for each version

Flow rate [l/min]	Left	Right	Total
Version 1	9,4	9,4	18,9
Version 2	10,9	10,9	21,7
Version 3	10,9	10,4	21,3

As one can observe from Table 3, version 3 is able to satisfy the constraint on the minimum flow rate required at maximum power, while including all the components needed for the system functionalities. This is therefore the final basic concept design selected for the project.

It is worth noting that this preliminary analysis has been carried out considering the pressure losses of the NEVS 93 EV car components, and only the OBC and the 400V-12V DC/DC converter will stay the same in the demonstration vehicle. Therefore, there is an intrinsic uncertainty in the results due to the assumptions made on the pressure losses through 3 out of 5 components and namely inverter, e-motor and 800V-400V DC/DC converter. In any case, the obtained results are sufficient to freeze the basic concept design of the circuit. In case of higher pressure drops, in fact, a new pump with a higher capacity will be acquired, keeping the layout unchanged. Moreover, the layout final definition is matter of Task 5.3 Cooling circuit layout definition and sizing, which will start at M21 and whose results will be documented with D5.3 System modelling for the evaluation of the final design, due at M22.

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5. Conclusions

The final output of this analysis is obviously a consequence of the main targets of the project, such as modularity, economic feasibility, reliability.

For sake of modularity, the layout with one pump for each module has been selected. The preliminary analysis has highlighted that the pump currently used in the baseline vehicle might be undersized for the module under development. Nonetheless, for sake of reliability, considering that the current pump has been tested and its effectiveness proved, the final choice for the coolant pump has been postponed until detailed data from the IDM components - on thermal loads and pressure drops - will be available.

Regarding the radiator, it seems to be oversized, since it is derived from the one of conventional internal combustion engines. This implies that there should not be any issue if the volumetric flow rate through the radiator increases with respect to its current operation, as expected for the F2 configuration.

Finally, for the other components (i.e. OBC, 400V-12V DC/DC and radiator fan) the devices currently used in the baseline vehicle will be employed, since off-the-shelve products for 800V OBC and 800-12V DCDC are not available. This will in turn avoid time and resources-related expenses, further contributing to economic feasibility and reliability.

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6. Appendix

List of abbreviations

IDM	integrated drivetrain module
WP	work package
EGL	mixture of 50% water + 50% ethylene glycol
RESS	Rechargable Energy Storage System (battery)
OBC	on-board charger
SWOT	strengths, weaknesses, opportunities and threats

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1. 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
2. D2.2 System specification of prototype, related Task 2.2 of WP2, submitted on November 2018. Deepak Singh, NEVS

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