

Scalable Complexity Simulation in the Electric Vehicle Thermal Management Development Process

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ABSTRACT

In order to provide efficient thermal management for an electric vehicle, the development of the cooling and conditioning system has to start early on in the overall product development cycle. This means that the first simulation models have to make do with relatively few actual data, mostly based on concepts and design studies. Accordingly the possible results are mainly useable for early on feasibility assessments.

With more data and more details available, these simulation models gradually evolve, until in the end the overall cooling system is modeled with a relatively high level of detail. This allows e.g. transient analysis of warm-up or cool-down runs, simulation of driving cycles, implementation and optimization of control strategies.

Although this basic workflow is true both for ICE and electric vehicles, for the latter specific topics like battery thermal management and HVAC integration add to the overall complexity. Especially the electric battery with its strong temperature constraints and its complex internal structure normally requires several modeling steps with increasing levels of detail during the development process.

We want to discuss:

Which data is required for different complexity levels of EV cooling system models?

Which conclusions can be drawn from the different models and how do they influence the overall development process?

How can continuous evolution of one simulation model during the product development cycle contribute to stable workflows?

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INTRODUCTION

Let us assume that we have the task to develop a cooling system for an electric vehicle. Our targets are to:

1. Prevent overheating of all involved parts (battery, electric motor / generator, power electronics and additional aggregates),
2. Achieve fast warm-up of cold-temperature-sensitive components (e.g. battery) in cold conditions,
3. Achieve fast warm-up of passenger compartment in cold conditions (and a convenient steady state temperature afterwards),

4. Achieve fast cool-down of passenger compartment in hot conditions (and a convenient steady temperature afterwards) and

5. Ensure highest possible energy efficiency of the cooling system (usage of waste-heat, reduced pump- and fan-power-consumption...) to improve overall vehicle range.

Especially the thermal conditioning of the battery will be a very critical topic.

We can reach these targets by:

1. Selecting a certain system layout: Depending on the thermal boundary conditions (temperature limits of components, amount of rejected heat, pump requirements...)

some system layouts will have clear advantages compared to others,

2. Selecting and sizing components for this system: Whereas the available space puts some constraints on the actual components sizes and arrangement, thermal requirements (and cost considerations) lead to the selection of specific types from specific manufacturers

3. Defining operating strategies which optimize the system performance: Even for fixed components in a fixed layout, the operating strategy (of pumps, valves, thermostats...) has a considerable influence on the system performance and efficiency.

The complete vehicle development process can be roughly separated into three phases (the names of these phases of course vary for different OEMs):

1. Concept Phase
2. Adjustment Phase
3. Prototype Phase

We will lead through this process and some typical simulation tasks based on the following example of an electric vehicle:



Figure 1. Example of an electric passenger car

We will use a battery with roughly 25kWh capacity, distributed to 200 battery cells, grouped to 10 modules. We will include an electric motor / generator with approximately 65kW peak performance, the vehicle has a target range of 200km.

All 1D simulations will be performed with the thermal management software KULI.

SIMULATIONS IN THE CONCEPT PHASE

In the first phase of the development process very few details are available about the real vehicle later on. Nevertheless it is possible to identify (and roughly quantify) the main heat sources and most critical cooling and heating

requirements. The basic boundary conditions for simulation models are given by the answers to the following questions:

1. What is the target power output from the electric motor(s) and how much rejected heat can be expected (based on estimated efficiencies)?
2. What is the target range of the vehicle and which battery technology will be used? What maximal C-rates (based on motor power and battery capacity) and therefore which maximal rejected heat has to be expected?
3. What are the expected thermal losses from power electronics (based on power requirement and standard efficiencies)?
4. What cooling and heating power will be required for the HVAC system (based on estimated cabin air volume and target market)... this will lead to additional battery loads (compressor, electric heating) and additional heat sources (condenser) and sinks (heater) in the cooling system?
5. What are the safety temperature limits for the battery and other electric components?

Considering these boundary conditions and using the available data, it is possible to set up a concept for the cooling and HVAC system and make some fundamental layout and design decisions. The basis for this will be mainly steady state simulation runs.

Steady State Concept Analysis of Temperature Levels and Energy Flows

In order to get all the required data for setting up a first steady state model, we answer questions 1 to 5 from the previous section.

1. In order to get some safety margins for real life operation, we will investigate a high load high velocity operating point of the car (these results will have to be reviewed again with transient analysis to prevent oversizing of the cooling system, of course). Target mechanical power output of the motor in the investigated operating point is 44kW (approximately 70 Nm at 6000 rpm). We assume a motor efficiency of 88%.
2. The battery will operate at 370V and have an internal resistance (later on described by a temperature and SOC dependent map) of around 0.3Ohm. This allows calculating the thermal losses from the required power output.
3. Power electronics will have an assumed efficiency of 92%.
4. The thermal load of the base AC system (without thermal loads from the battery) is set to 3kW. Electrical power requirements for all auxiliaries are lumped to 4.5kW.

5. Steady state safety limits are 80°C for e-motor and power electronics and 30°C for the battery. We assume hot ambient air temperature levels of 40°C.

This data allows us to set up a cooling system according to [figure 2](#).

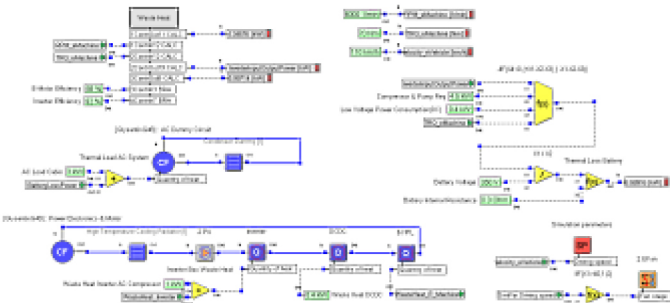


Figure 2. Steady state cooling system model

The main focus here is on the high temperature cooling circuit and the air-flow through the cooling package. The low temperature circuit of the battery is not modeled explicitly, but the battery heat load is added directly to the AC-system. This helps us to work without data for the chiller (normally coupling the low T circuit to the AC system parallel to the cabin evaporator). This prevents us from making temperature predictions for the battery, but allows an analysis of the energy flows (thermal and electrical) and an evaluation of the temperature levels for the rest of the system.

Starting a simulation run yields the results shown in [figure 3](#).

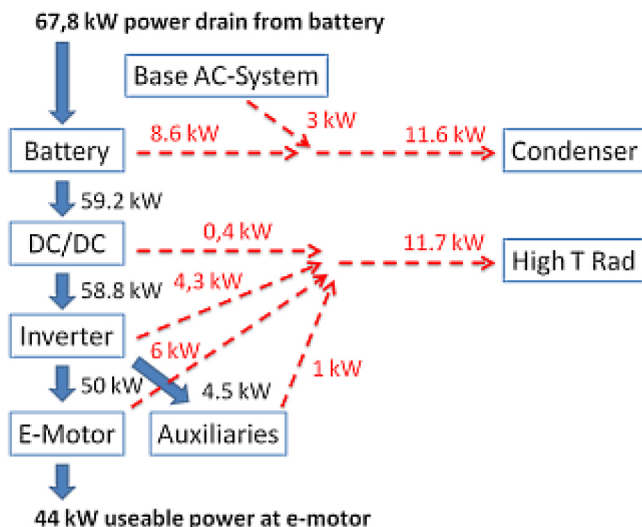


Figure 3. Steady state energy flows for a high-load and high-velocity operating point

Furthermore we obtain temperature levels between 78°C and 80°C for DC/DC, inverter and electric motor. This lets us draw some conclusions:

The temperature levels show that the basic sizing of the radiator and the coolant pump in the high temperature circuit

is good and can also handle the additional heat load from the AC-system (the condenser is located in front of the high T radiator).

The battery produces a significant thermal output in this operating point. For lower ambient temperatures this will be handled by a separate low T radiator, but for high temperatures (like 40°C) this causes high additional loads for the AC system. This will have to be considered in the sizing of the condenser and the compressor later on.

Auxiliaries and AC system together produce considerable thermal and electrical loads. When trying to improve the overall efficiency of the system later on, this is where we should focus.

SIMULATIONS IN THE ADJUSTMENT PHASE

After the exterior vehicle design freeze and with many details about the underhood layout fixed, both geometrical restrictions for the cooling system components and air-flow data (from 3D CFD simulations) become available.

This allows setting up an improved cooling system model which will be used for component target setting and component comparison / selection.

In the beginning of this phase the focus is still on steady state simulation, but later on (as more and more data becomes available) transient simulation runs are performed as well.

Transient Verification of the Steady State Cooling System Concept

In order to upgrade the steady state concept phase simulation model for transient capabilities, the following data is required:

1. All thermal capacities in the cooling system have to be considered. This involves mainly the battery mass and the masses of power electronics and electric motor, but the thermal inertia of the coolant fluid itself must not be neglected, too.

2. In order to get transient e-motor operating points for the simulation of a driving cycle, at least some simple driving simulation has to be performed. This can be either done with a dedicated driving simulation tool or (in a simplified way) within the thermal management simulation environment itself.

3. All design decisions which are already fixed and their implications on the cooling system have to be considered. E.g. if the underhood layout is fixed, maximal sizes for coolers and radiators are known.

4. All additional details available about the cooling system itself should be included in the simulation model as well. This could be e.g. thermostat characteristics or also operating strategies for pumps or compressors.

The result will be a simulation model similar to [figure 4](#).