Thermo-Engineering- Simulation-based Modular Development Process for Thermal Management of Electric Vehicles

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Abstract: In the various phases of the vehicle development, different numerical simulation tools are used in various departments. Focusing on the development of the vehicle thermal management system, there are also multiple numerical simulation tools been used for performance and function prognosis at part, component, module and system level. To enable the optimization of all heat and energy flows, a coupling of the thermal simulation tools with the other vehicular subsystems and the environment is indispensable.

TheSys built up a co-simulation environment integrating thermal 0D-/1D- and 3D-simulation tools for powertrain cooling and HVAC, been coupled to other vehicle subsystems. Main scope is to improve energy efficiency by thermal system and intelligent control measures. Cooling performance requirements have to be met while minimizing the energy requirement for vehicle cooling and air conditioning. The superordinate, modular structure of the simulation model enables modifications of the circuit architecture and component dimensions.

The co-simulation was developed within a French-German research project "InnoTherMS". Scope was the design of an innovative cooling system for an electrically driven, urban delivery truck. The truck was equipped with two temperature-controlled transport compartments for hot (warm meals) and cold (cold drinks) goods. These thermal compartments were coupled to the vehicle cooling system as well as to the cabin-HVAC within one integrated vehicular thermal management architecture. It utilizes a heat pump and thermal storages. As a result of the project, the electric driving range was increased by around 10% compared to a reference vehicle.

1 State of research

1.1 Thermal Management

Thermal management is the control of heat flows in the vehicle. The task of thermal management is to operate components in the respective optimum temperature range and to generate comfortable temperatures for the occupants in the cabin.

A thermal management system in an electric vehicle is generally more complex than in conventional vehicles with combustion engines. For example, the electric axle must always be cooled, while the battery must either be cooled or heated depending on the situation. Also, the various electric components often require different coolant temperatures levels, which can lead to separated low and high temperature circuits. In addition, waste heat from an internal combustion engine is no longer available for heating the cabin, so energy-efficient systems such as a heat pump are used for this purpose.

To transport the heat in the vehicle and provide the required temperatures, the refrigeration circuit and the different cooling circuits must interact optimally. The interconnection of the circuits changes depending on the heating or cooling requirements, which results in different operating modes and complex control strategies.

In the cooling circuits, cooling water transports heat from where it is generated to where it is needed in the vehicle. Due to its high specific heat capacity, the cooling water can absorb a lot of heat in a very small space, which is necessary, for example, for effective cooling of the electric axis or the battery.

A refrigerant circulates in the heat-pump or air-conditioning circuit, which can be either liquid or gaseous. The evaporation (transition from liquid to gaseous) of the refrigerant generates a cooling capacity that enables cooling even below ambient temperature. This well-known principle for air conditioning the cabin in summer is also used to cool the battery at very high outside temperatures.

In addition, the heat released during condensation (transition from gaseous to liquid) can be used to heat the cabin or battery in the winter. The refrigeration circuit is driven by an electric refrigerant compressor, which compresses the refrigerant to the desired pressure so that evaporation and condensation take place at the respective desired temperature.

Further challenges are system reliability under extreme operating conditions and in widely varying application profiles worldwide, as well as cost requirements and package constraints.

1.2 Methods

The rising complexity of the thermal management system and its various control units also requires new methods and approaches for the system development process, making virtual methods indispensable. CAE (Computer Aided Engineering) has become an integral part of today's development process. In addition to an increasing number of target parameters, there is a high time and cost pressure, which makes it necessary to increase efficiency. But how do I find the right simulation approach for my application among the multitude of available tools and methods? When can I investigate a system as a stand-alone system and when is the consideration of system interactions required?

The above questions can be answered with the modular development process “Thermo-Engineering” by our experts at TheSys with decades of professional experience, who understand the development, application and production requirements of manufacturers and supplier companies.

In simulation projects often the most difficult part is to know the limits of the simulation. Thermodynamic simulation ranges from the microscopic level of the radiator fin and tube, over the heat transfer network of the radiator, to the macroscopic level of the underhood cooling module, the cooling system and air conditioning system in the vehicle. The different simulation approaches are clustered as follows:

0D:

The 0D simulation does not include a spatial but only a temporal dependency. Our in-house developed software "TheSim" enables the development of new fins, turbulence inserts and tubes for cooling networks with prediction of performance and pressure drop. It also enables the adaptation of heat exchangers to modified installation space and operating requirements. The method is also applicable for 2-phase components such as condensers and evaporators.

1D:

For the design and control of the overall system under real load collectives, 1D simulation is used. The objective is to develop the system architecture and to design the cooling components. Also, to define the control strategy, to examine the limits of use or to develop an efficient operating strategy. Thus, at an early stage in the development process, long before prototypes are necessary, this can be steered in a meaningful direction. In the course of this, the required heat exchanger for the heat exchange with the environment is also defined. Common tools also used by TheSys for 1D simulation of thermal management systems are GT-Suite and KULI, Matlab/Simulink is added for the control unit development.

3D:

If the project faces installation space restrictions for example, the only option is to improve the heat transfer to the environment. The geometry optimization of fins, radiator network, radiator and cooling air or coolant routing is done with 3D simulation (CFD = Computational Fluid Dynamics). It can be used to examine in detail whether the selected component will also provide the required cooling performance in the installation situation of your specific application. By visualizing the flow in the room, dead spaces and other disturbing factors caused by installation resistances can be identified and eliminated. Due to increased requirements in the project or to increase the efficiency of the system, the optimization of the heat exchanger in the next development step. Another common application for 3D Simulation is the use of internal cabin flow investigations, to improve the passenger thermal comfort.

Co-Simulation:

Using co-simulation, the thermal management system and passenger compartment can be coupled with other subsystems and control units in the vehicle. Through the interactions of thermal management, powertrain and vehicle, all energy and heat flows are balanced, and the total energy demand can be optimized. This will decrease the overall energy consumption and increase the driving range of the vehicle.

The switch-on times of pumps and fans have a considerable influence on the overall system efficiency. Since complex interactions, e.g. with the self-heating of the battery, play a major role here, the use of a co-simulation is now necessary. The battery supplier has already developed such a model for his battery; now it is necessary to link this with the cooling model. In this way, it can be ensured that the current values such as temperatures, heat inputs, etc. are exchanged in each time step of a transient simulation.

Digital twin:

The concept of the "digital twin" describes the online coupling of the vehicle simulation with the vehicle test. During cooling performance measurements on the vehicle on the chassis dynamometer, driving speed, tractive force and ambient temperature are imposed on a simultaneously running thermal vehicle simulation. Through an automated comparison of the measured values (actual condition) with simulation results (expected condition), it can be detected at an early stage whether there are deviations. Discussion, testing and, if necessary, modification of the measurement program is possible in a timely manner. The medium-term goal is to build a simulation model in real-time with availability of the results at the end of the test.

2 French-German Research Project InnoTherMS

With an innovative thermal management system, the Franco-German research project InnoTherMS aims to reduce the energy consumption of electric vehicles to the bare minimum. As part of the project, a virtual, centralized, intelligent and predictive thermal management tool was developed for this purpose. It is based on simulation and modeling software for the cooling circuit and takes the thermal storage system into account. The InnoTherMS solution, which is particularly innovative, allows predicting and controlling the heating or cooling of an electric vehicle while consuming as little energy as possible, maximizing autonomy and ensuring the thermal comfort of passengers. The technologies developed for the InnoTherMS project are expected to improve the ranges of electric cars by at least 10 percent.

The German partners in the project include Fraunhofer, GreenIng, Esslingen University of Applied Sciences and TheSys. On the French side, the following partners are participating in the project: CETHIL (INSA Lyon), IFP Energies Nouvelles, LAGEPP (Université Claude Bernard Lyon 1), Saint Jean Industries and SEGULA Technologies. InnoTherMs benefits from public funding from the Auvergne-Rhône-Alpes region (France) and the Federal Ministry of Education and Research (Germany). TheSys was responsible for the development of the thermodynamic concept with evaluation of the range increase based on the whole vehicle simulation.

2.1 Customer Usage Profile

The transport and delivery of hot food and cold beverages to defined stations was specified as the usage profile (usage profile "remote kitchen"). Superimposed are road, traffic and weather profiles with influences of road gradient, driving speed, ambient temperature and solar radiation. In addition to the temperature control of the food, the temperature of the passenger cabin, battery and drive train must also be controlled.

2.2 Vehicle Thermal Management and Predictive Operation Control

From the definition of the customer usage profile, the required functionalities of the vehicle thermal management system emerged. The system architecture includes a high temperature (HT) coolant loop and low temperature (LT) chiller coolant loop coupled by a heat pump. The battery is tempered in a separate coolant circuit, which can be coupled to the HT or LT circuit via a shell-and-tube cooler. In addition, heat and cold accumulators as well as various auxiliary heaters are used.

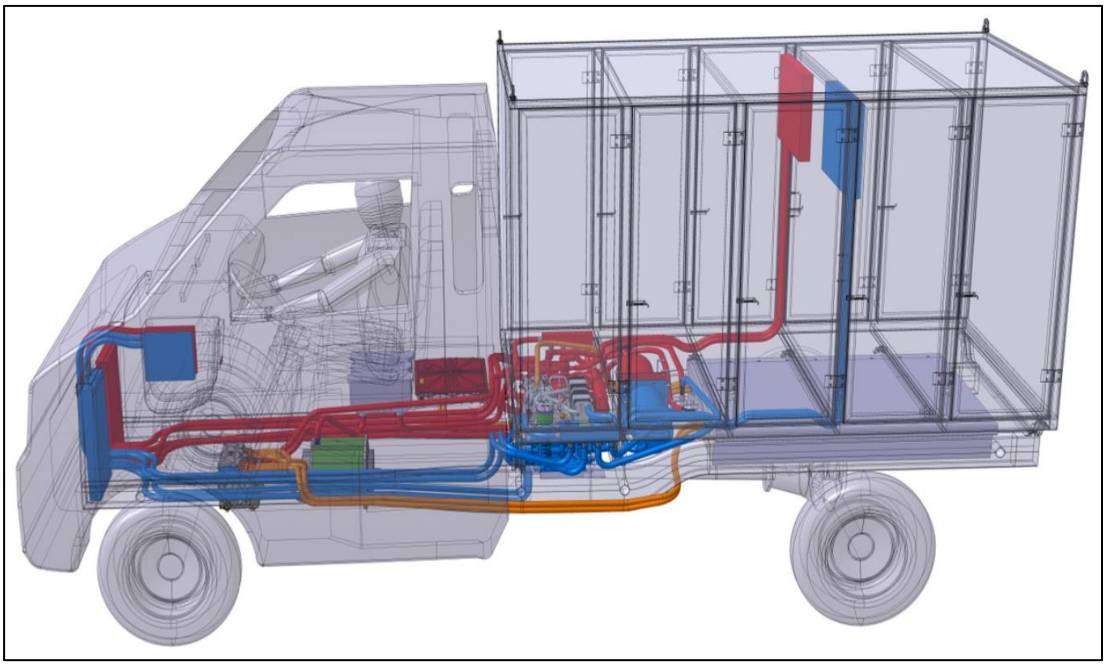

Figure 1: CAD-Model of the electric CEP (courier, express, parcel) vehicle (Source: GreenIng)

The operating control system ensures that the target temperatures of the battery, powertrain and passenger compartment are reached as quickly as possible after the start of the journey and maintained in the respective comfort temperature range for the duration of the journey. At the same time, the hot food must be prevented from cooling to below 65°C, while the cold drinks are cooled to below 8°C. The overriding objective of the operating control is to minimize the electrical energy required for the journey. The potential of a predictive operating strategy is also taken into account.

2.3 Sub-models and functional coupling

The project partners provided simulation sub-models for the hot/cold cabin and cargo compartment (Segula) and battery cells (CETHIL) from different simulation tool platforms, which were integrated into the GT-Suite vehicle model as part of a co-simulation with Matlab/Simulink. SJI provided the basic designs of the battery housing and the two thermal accumulators. The transfer to the corresponding GT submodels and integration into the overall vehicle model was also carried out by TheSys. The control system was provided by LAGEPP and IFPEN and adapted to the thermodynamic overall vehicle model in many iteration stages. This also included iterative changes to the model, component parameterization and control strategy.

The "Battery" submodel (CETHIL) provides the waste heat flow of the battery as a function of the electrical power (discharging, charging), the cell temperature and the SOC. The battery model is included as an FMU model in GT-Suite.

In the "cabin" submodel (SEGULA), the respective local environmental conditions such as air temperatures, flow velocities and also the CO2 content of the air are calculated for the driver and front passenger and a comfort value PPD is determined from this. For the overall model, however, only the average cabin air temperature was taken into account. The thermodynamic interface between the cabin model and the overall vehicle is the radiator or cold air heat exchanger, through which a mixture of cabin exhaust air (recirculation mode) and/or ambient air (fresh air mode) flows. The resulting air temperature depends on the coolant flow and is returned to the cabin. The cabin model is generated as a DLL file from Matlab-Simulink and integrated into GT-Suite.

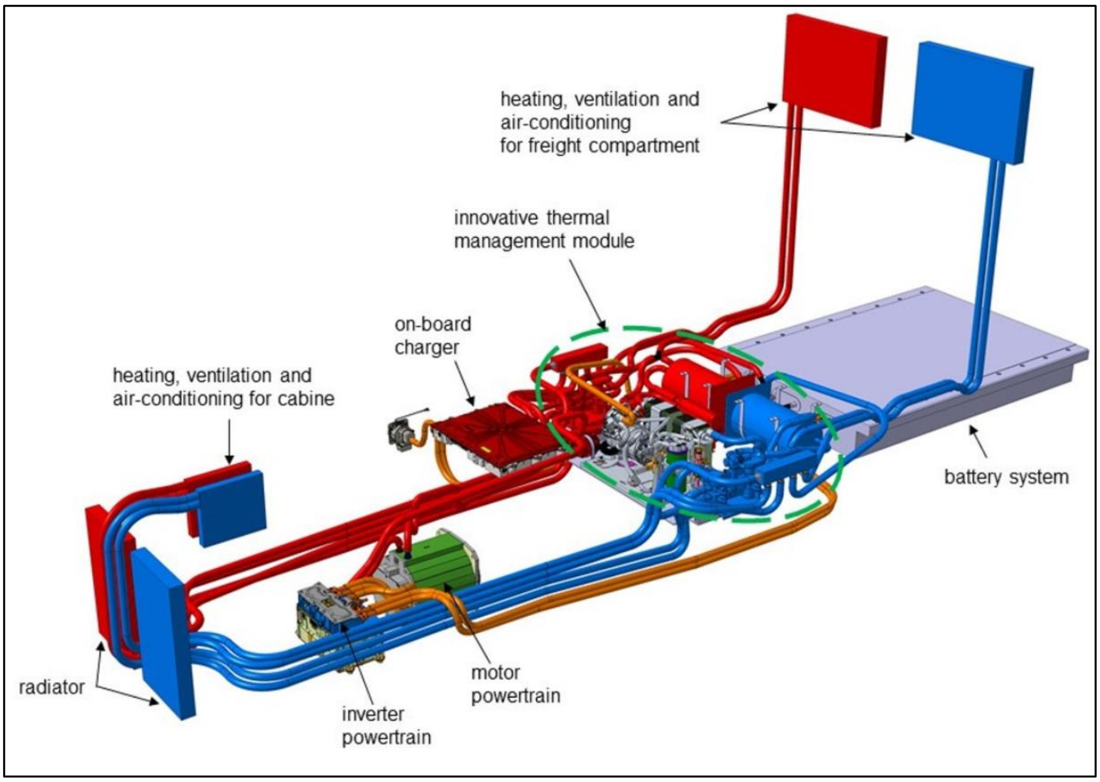

Figure 2: Coolant and Refrigerant Circuits of the vehicle (Source: GreenIng)

The submodel "cargo hold" (SEGULA) was constructed analogously and also integrated as a DLL file. It consists of two temperature-controlled cargo holds "cargo hold/hot" and "cargo hold/cold". Here, the thermodynamic interface is also represented by a cooler module in the hot and in the cold area, which are supplied with air by an electric fan.

The control (IFEN/LAGEP) was developed in parallel in a fast-running Matlab Simulink model, which first had to be aligned with the GT model. After alignment, the structure and parameters of the control of IFPEN could be developed with this model. The resulting CoSim Controls file was then integrated into the GT model by TheSys and tested. Functional safety requirements, for which EMI was responsible, were implemented as operating limits in the control system and prioritized depending on probability of occurrence and risk of damage in the control intervention.

The thermodynamic simulation model was built in a co-simulation environment to integrate software submodels of the project partners. Matlab/Simulink acts here as the master.

2.4 Results of the InnoTherMS project

Based on various previously defined usage profiles for hot food and cold beverage transportation, thermodynamic condition of components and passengers as well as the energy demand of a target vehicle were simulated. The calculated energy demand was used to predict the electric range of the target vehicle compared to a thermodynamic reference vehicle. For two usage profiles "Stuttgart" and "Lyon", it was possible to determine an average annual range increase of approx. 13% weighted over the ambient temperature.

Result: A range increase of 10% for a series vehicle is plausible. A conversion of the energy demand in the Stuttgart driving profile to the electric range of the vehicles yields plausible consumption values and allows a quantification of the range differences.

	Target vehicle	**Reference vehicle**	**Range difference**
Summer	30,4 kWh/100km	30,2 kWh/100km	- 1%
Spring	22,1 kWh/100km	27,5 kWh/100km	+25%
Winter	28,9 kWh/100km	34,3 kWh/100km	+19%

3 Thermo-Engineering

As an expert in vehicle thermal management, TheSys develops new cooling systems, heat exchangers and cooling components for the vehicle drive and passenger compartment air conditioning. In doing so, our solutions meet the specific requirements of electrified powertrains in passenger cars, commercial vehicles and off-road vehicles with traction battery and fuel cell. The increasing use of heat pumps leads to a close coupling of powertrain cooling and vehicle air conditioning. For our customers, global vehicle manufacturers and suppliers, this results in new cooling system architectures and heat exchangers with targeted dimensioning and specification of cooling components.

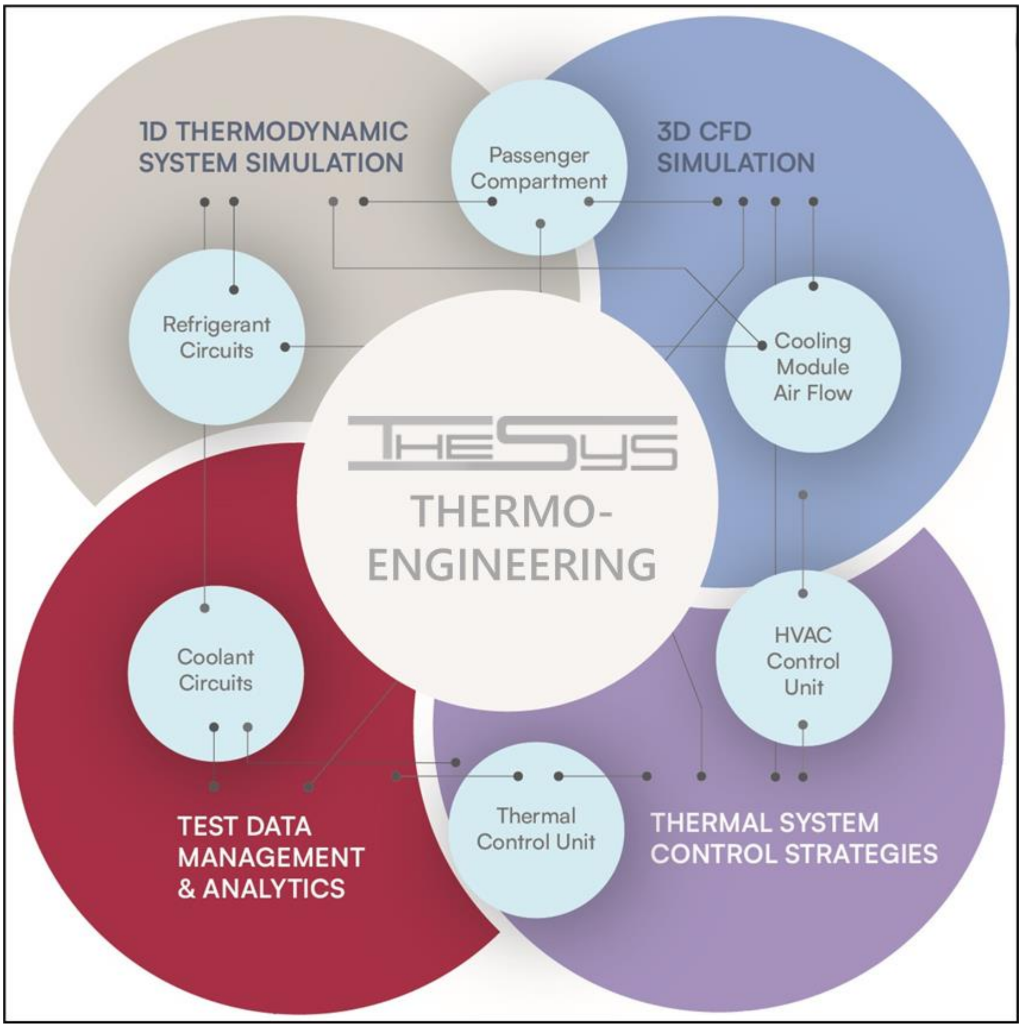

Figure 3: TheSys Thermo-Engineering Development Process

TheSys provides its customers with efficient development methods, which is summarize under the therm “Thermo-Engineering”, which reduces development times and costs in testing. An integral part of this process is the “Thermo Configurator”, which enables the application, series and sales departments to design the cooling system without the need for specific simulation skills.

Special emphasis is placed on the efficient control of all energy and heat flows in the vehicle. Operational control is developed in a co-simulation environment in which the thermal system is coupled with other subsystems of the vehicle. The system simulation is also the basis for in-vehicle operational control incorporating Car2x information and predictive strategies.

Vehicle simulation models are usually so complex that they can only be operated by a few engineers with many years of experience. For our customers, this often leads to significant personnel bottlenecks, and projects get behind schedule. What would it be like if there were a user interface that allowed application engineers, for example, to configure the right cooling system for their application independently without software training? How about if salespeople from supplier companies could quantify the function and customer benefit of their product in the target vehicle?

Our vehicle configurator allows the selection of vehicle, drive, cooling circuit and cooling component from an approved library, similar to the configuration of a new car on the Internet. It prevents unacceptable combinations and creates the associated vehicle simulation model fully automatically in the background. Selection of the driving route and the result is output in a standardized form. Our customers have been using the configurator for years and it is constantly being further developed. Currently it allows the selection from more than 250 circuits, components or even control units for more than 30 different vehicle types. Depending on the focus of your investigation, you can choose between detailed and simplified models. If a subsystem is not relevant it can be replaced by dummy models, to ensure that the overall simulation run time is as fast as possible.

A good simulation model is only as good as the data on which it is based on. The ability to validate the models is essential for the validity of these elements. This modular simulation environment also provides an interface to read and process measurement data and to calibrate the models based on them. The possibility of coupling the same control units as used in the vehicle, enables transient simulations which can be easily compared to measurement driving cycles.

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