Holistic System Simulation to address Thermal Management Challenges in Fuel Cell based Mobility Platforms

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Abstract: Thermal security of fuel cell powertrains is very challenging as the optimum operating condition of a fuel cell lies in a very small temperature range and is much lower than for combustion engines. The lower optimum level of the coolant temperature of a fuel cell powertrain makes the heat rejection to the ambient challenging as it leads to smaller temperature differences between the coolant and ambient at the heat exchangers that are used to reject the heat to the ambient. Therefore cooling system concepts need to be re-designed, optimized and verified for dynamic loads to address those thermal management challenges.

In this paper a holistic system simulation methodology is presented to address the thermal management challenges of a fuel cell powertrain of a heavy duty truck at hot ambient conditions and long haul missions. The holistic system simulation methodology includes a design comparison of different heat exchanger layouts, the optimization of the selected heat exchangers, and finally the verification of the optimized heat exchanger stack layout for dynamic loads by performing transient drive cycle simulations.

1 Introduction

The transportation sector contributes with around 23% to the global CO2 emission with freight transportation on road as one of the major contributors [1]. As over three quarter of the inland freight transport in the EU is performed by road with heavy duty trucks [2], the reduction of tailpipe emissions of heavy duty trucks is crucial to reach the emission reduction goals defined in the European Green Deal.

Therefore alternative powertrain solutions like fuel cell powertrains are investigated and will play a signification role for the future reduction of greenhouse gas emissions especially in the road freight transportation sector [3].

In comparison to the currently used diesel engine, fuel cell powertrains have no tailpipe emissions and have a higher energy efficiency. In comparison to battery powertrains they are expected to offer a larger range at lower vehicle weight and a faster refueling [3]. Global truck companies like Daimler Truck [4], Volvo Trucks [5], MAN [6], PACCAR [7], and others are focusing on the research and development of a fuel cell powertrains for trucks.

Most truck fuel cell powertrains use a proton exchange membrane fuel cell (PEMFC), which has advantages such as low operating temperature, high energy conversion efficiency, and swift start-ups. However the lower operating temperatures make the thermal management of fuel cell powertrains challenging. Further high temperature gradients in the fuel cell stack during dynamic load variations have a negative impact on the fuel cell stack as they cause thermal stresses and stack material degradation [8].

Therefore it is mandatory to develop a thermal management system that is capable of a fast and efficient heat rejection and obtains the optimum operating temperature even under dynamic load changes to ensure thermal security among all operating conditions. A holistic system simulation of the thermal management system of a fuel cell truck enables fast analysis, comparison and optimization of different cooling concepts and system layouts. Further it enables optimization of selected components of the cooling circuit and verification of the optimized design integrated into the complete fuel cell truck system during dynamic loads by transient drive cycle simulations.

2 Fuel Cell Truck System Simulation Model

For the simulation based development methodology a GT-SUITE system model of a fuel cell truck is used. The simulation model in Figure 1 includes a detailed fuel cell powertrain model including two PEM fuel cell stacks, a battery, an electric motor and a power converter. The fuel cell powertrain is connected to a vehicle model of the truck for calculation of the longitudinal vehicle dynamics. Further the simulation model includes a detailed thermal management system that is tightly coupled to the fuel cell powertrain.

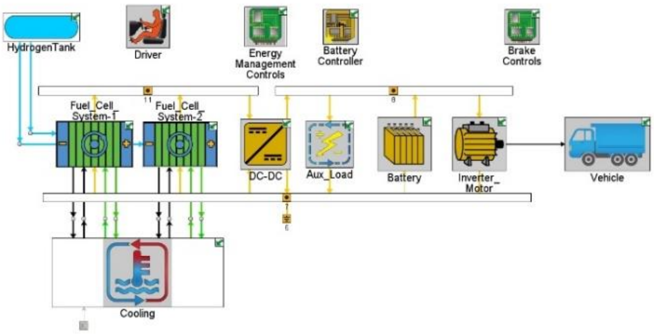

Figure 1: GT-SUITE System Simulation Model

2.1 Powertrain System Model

The powertrain system in Figure 2 includes all relevant flow, electrical, electro-chemical and controls components to enable detailed and realistic representation in the simulation model.

The electric model is composed of one electric motor with inverter efficiency integrated, a 80 kWh battery, a DC/DC converter and two fuel cells stacks with 600 cells each, an active surface area of 250 cm² and a maximum rated power of 110 kW. More details on the fuel cell system can be found in section 2.3. The fuel cell stacks are fueled with H2 which comes from the H2 tank of the model.

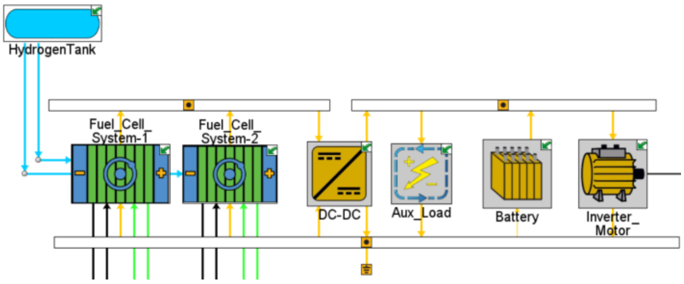

Figure 2: Fuel Cell Truck Model (Electrical Part)

The torque demand and the speed of the electric motor is calculated using the mechanical vehicle model and depends on the drive cycle profile imposed in the simulation model. A driver model is included in the system model to model a realistic driver behavior.

The power split between the battery and the fuel cell stack is defined based on the SOC of the battery and minimum and maximum limits for the power and the ramp rate that can be supplied by the fuel cell stack. Mostly the battery supports the fuel cell at high dynamic loads.

In addition, the electrical powertrain model takes into account the power demand of all the accessories of the different parts of the fuel cell truck, including the fuel cell stack compressors, H2 recirculation pump and cooling pump. This enables to calculate a full system power balance.

2.2 Vehicle System Model

The mechanical vehicle model shown in Figure 3 directly interacts with the electrical powertrain model. It includes a truck body, axles, tires and a differential. The truck body consists of a main body and a trailer. Each part is defined by its weight and its aerodynamic properties. With this information the longitudinal motion of the truck is calculated for the different driving profiles.

The axle and tire model include the traction and rolling resistance characteristics. Finally, the differential is an open differential where the axles and the electric motor can operate at different speeds.

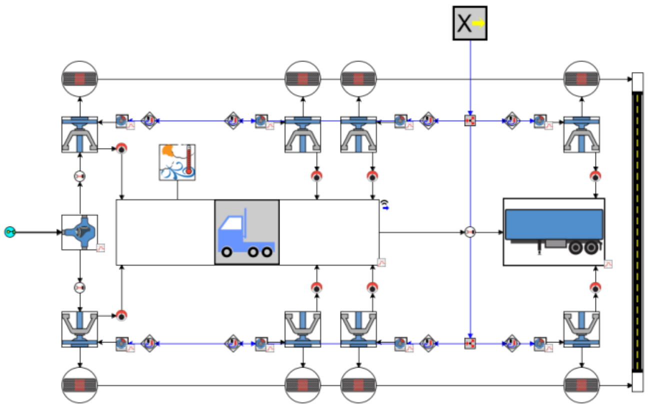

Figure 3: Fuel Cell Truck Model (Mechanical Part)

2.3 Fuel Cell System Model

The fuel cell system model in Figure 4 is composed of a fuel cell stack, coupled with the anode loop, the cathode loop, and the cooling circuit. Further the fuel cell stack is directly connected to the electrical circuit.

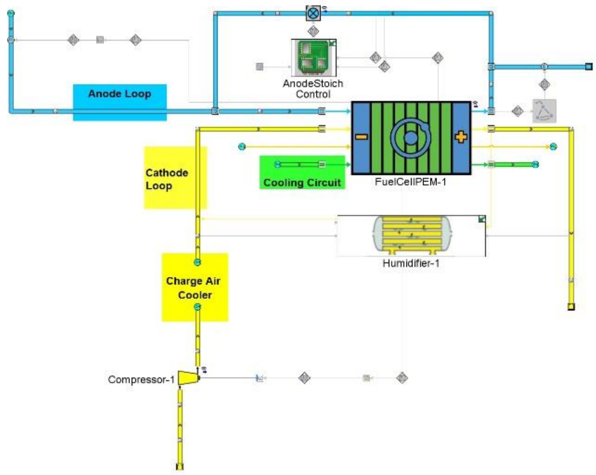

Figure 4: Fuel Cell Balance of Plant Model

The anode loop starts at the H2 tank. A pressure regulating system including valves and controls lowers the 700 bar tank pressure to the anode loop operating pressure. The anode loop simulation model also includes the recirculation blower, stoichiometry control and the purge valve system and controls. This allows to accurately account for the energy losses that are driven by the purging strategy selected for this powertrain model.

The cathode loop includes a compressor, a humidifier and an indirect charge air cooler linked to the cooling circuit. The compressor is controlled based on the fuel cell current power demand and the cathode stoichiometry.

The fuel cell stack is modelled using GT-SUITEs predictive electrochemical model, accounting for the physical characteristics of all layers which compose the fuel cell stack (gas diffusion layers, catalyst layer, membrane, bipolar plates). The fuel cell stack also includes a thermal model which is connected to the cooling circuit and a flow model to model consumption of H2 at the anode and O2 at the cathode, gaseous species crossover, and water crossover [9].

2.4 Cooling System Model

The cooling system of the fuel cell truck in Figure 5 consists of two cooling circuits. A high temperature (HT) cooling circuit to ensure the thermal security and best operating condition of the two fuel cell stacks. In addition two indirect water charge air coolers are connected to the high temperature coolant circuit to cool cathode side airflow following its compression.

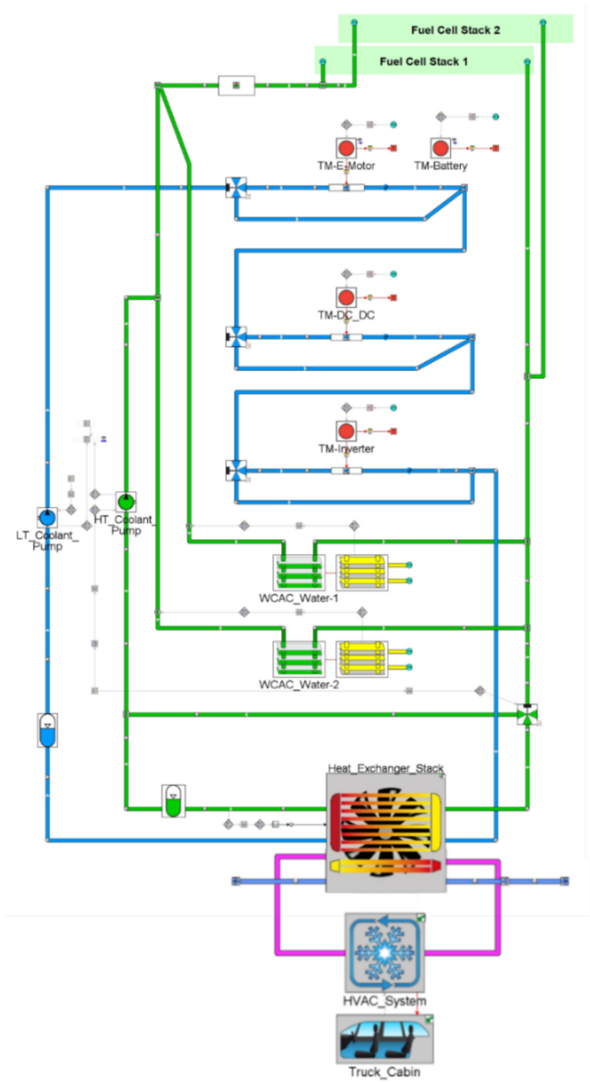

Figure 5: Fuel Cell Truck Cooling System Model

The second cooling circuit is a low temperature (LT) cooling circuit to ensure the thermal security of the electric motor and other power electronic components.

As the battery of the fuel cell truck is used only to support the fuel cell powertrain in phases of highly dynamic load changes its heat can be rejected to the environment using an air cooling concept to ensure the thermal security of the battery. The cooling system model includes an air-conditioning system for thermal conditioning and dehumidification of the truck cabin as well.

The heat exchanger stack in Figure 6 is modelled in GT-SUITEs integrated 3D modelling environment COOL3D. It includes the condenser of the air-conditioning system, the HT and LT radiator of the cooling system and a cooling fan. Further it includes a blockage at the inlet to model the underhood inlet grille. The two radiators are mounted vertically with the coolant inlet at the top of the heat exchanger. The condenser is mounted horizontally.

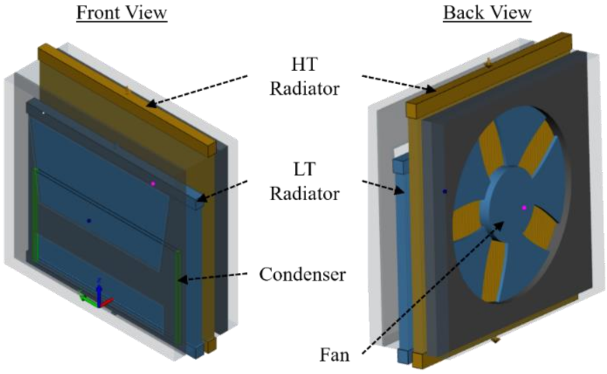

Figure 6: Heat Exchanger Stack Model

The cooling systems includes control functions to control the temperature of the fuel cell stacks and the other fuel cell powertrain components. The input signal of the electric HT coolant pump is controlled by a PID controller which targets the fuel cell stack outlet temperature of 75 °C for best operating conditions of the fuel cell. In addition to that a bypass valve is used to bypass the HT radiator for fast heat-up of the fuel cell stacks at low initial temperature conditions and to prevent low fuel cell temperatures and dynamic loads. The goal of the controls is to keep the fuel cell stack temperature in a range of 65 to 85 °C.

The input signal of the electric LT coolant pump is controlled by a PID controller which targets the temperatures of the electric motor and the power electronics components. All components can be bypassed to ensure a fast heat-up of the components at low initial temperature conditions.

The fan controller controls the fan speed and therefore the air flow through the heat exchanger stack in combination with the vehicle speed. It targets different coolant outlet temperatures of the HT and LT cooling circuit to ensure a suifficient temperature gradient between the cooling temperature and ambient temperature at all operating conditions for efficient heat rejection to the ambient air.

3 Simulation based Optimization of the Cooling System

The fuel cell truck system simulation model described in the previous chapter is used to optimize the cooling system of the fuel cell truck. The goal of the simulation based optimization of the cooling system is to ensure the thermal security of the fuel cell powertrain, especially of the fuel cell stacks.

As this study focuses on trucks that are used for long haul routes, constant speed driving at 80 km/h is used as steady-state design condition in the first stage of the simulation based development. As hot ambient conditions cause the smallest temperature gradients at the heat exchangers of the heat exchanger stack, an ambient temperature of 45 °C is used to ensure suifficient heat rejection at hot ambient conditions.

3.1 Heat Exchanger Stack Component Selection

The first step of the simulation based development is to find the heat exchanger layout that is best suited to reject the heat of the fuel cell stacks and the other powertrain components by comparing different heat exchanger layouts. Figure 7 shows the two different designs of the heat exchangers stack with different heat exchanger layouts. The single pass design uses single pass heat exchangers as LT and HT radiator. The dual pass design uses heat exchangers with 2 passes as LT and HT radiator.

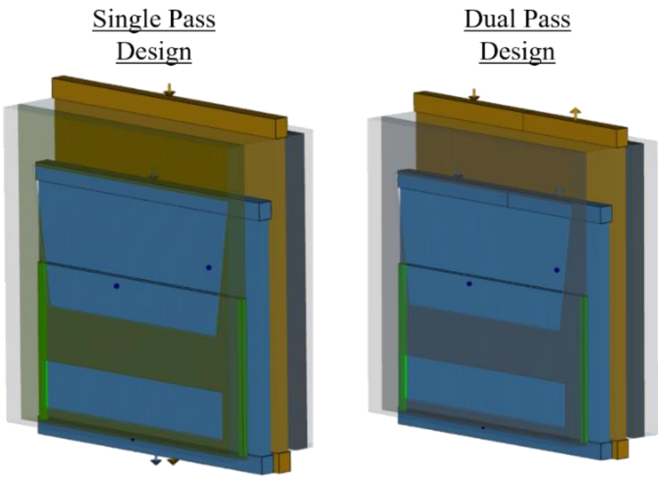

Figure 7: Single and Dual Pass Heat Exchanger Stack Design

Steady-state simulations at a constant vehicle speed of 80 km/h and an ambient temperature of 45 °C are performed to compare both designs under high load conditions. The coolant pumps and the coolant fan are operating at maximum speed to analyze the cooling systems performance at maximum power conditions.

As can be seen in Figure 8, the dual pass design is better suited to ensure sufficient heat rejection at the fuel cell stacks, whereas the single pass design shows advantages for the cooling of the other powertrain components. Therefore a dual pass heat exchanger is used for the HT radiator and a single pass heat exchanger is used as LT radiator.

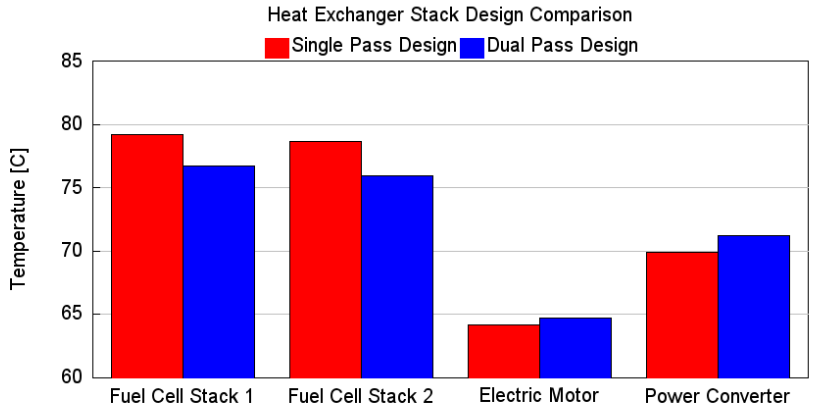

Figure 8: Heat Exchanger Stack Design Comparison

However with neither of the designs, the target fuel cell stack temperature of 75 °C is reached. Therefore the size of the heat exchangers is optimized in a next step.

3.2 Heat Exchanger Component Optimization

To optimize the size of the LT and HT radiator, the Integrated Design Optimizer of GT-SUITE is used. The maximum size of the heat exchangers is limited by the available design space of 950 x 950 mm. The size of the two radiators is optimized with respect to the fuel cell stack temperature and the DC/DC converter temperature.

The HT radiator is located downstream of the LT radiator in the heat exchanger stack. Therefore the size of the LT radiator directly influences the free-streaming area of the HT radiator. Therefore the size of both radiators needs to be optimized together. Because the second radiator has two passes and the distribution of the pipes between the two passes needs to be defined for the optimization, the number of tubes of the first pass is optimized and the number of tubes of the second pass is the number of tubes of the first pass minus five.

Figure 9 shows the optimization results of the LT radiator. The best optimization design is marked with a large cross.

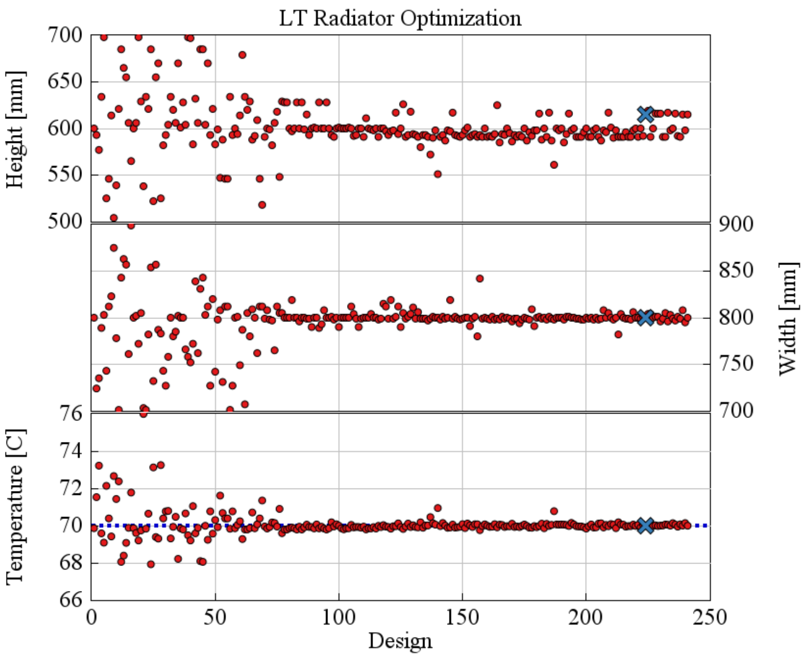

Figure 9: LT Radiator Optimization Results

Figure 10 shows the optimization results of the HT radiator. The best optimization design is marked with a large cross again.

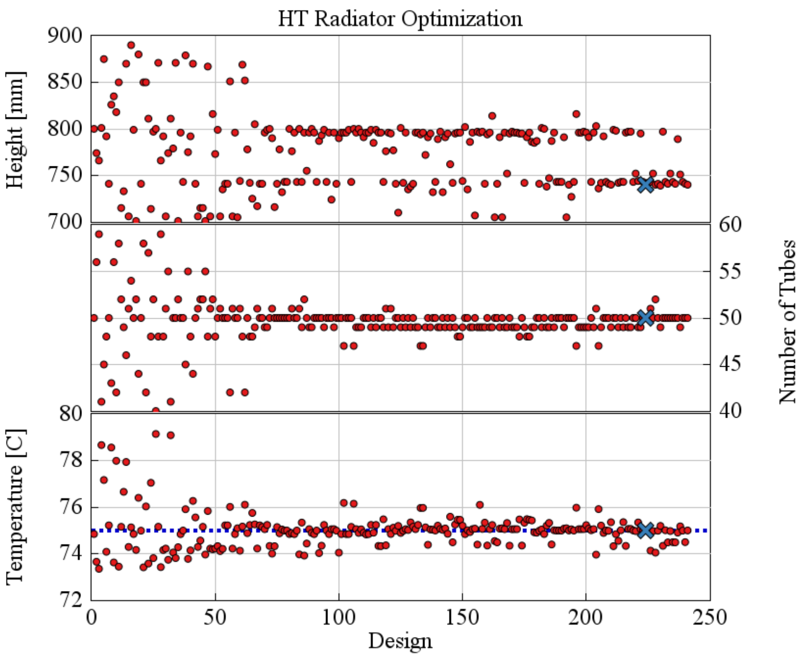

Figure 10: HT Radiator Optimization Results

The optimization results in a LT radiator size of 615 x 800 mm and a HT radiator site of 740 x 756.5 mm. As can be seen in Figure 9 and Figure 10, the target of 75 °C of the fuel cell stack outlet temperature and the target of 70 °C of the DC/DC converter outlet temperature are both reached with the optimization result.

3.3 Cooling System Verification through Drive Cycle Simulations

After the optimization of the LT and HT radiator of the heat exchanger stack, the thermal security of the fuel cell powertrain for dynamic load changes is verified by running transient drive cycle simulations. Like the steady-state analysis and optimization, the transient drive cycle simulations are performed at hot ambient conditions and therefore at an ambient temperature of 45 °C. The goal is to keep the fuel cell stack temperature within a range of 65 to 85 °C throughout the whole drive cycle whereas some short peaks to 90 °C or short drops to 60 °C are considered acceptable.

As drive cycles, two VECTO mission profiles long haul and regional delivery are used whereas the long haul is considered the most relevant one for the fuel cell truck in this study. The VECTO mission profiles have a total distance traveled of 100 km and are available on the website of the European Commission [10]. Further a real driving route of the Brenner Pass created with GT-RealDrive is used to test the cooling system at real driving conditions.

The simulation results of the VECTO mission profile long haul in Figure 11 show that the designed cooling system with the optimized heat exchanger stack is capable of keeping the fuel cell stack temperature and the DC/DC converter and electric motor temperature in the desired temperature range.

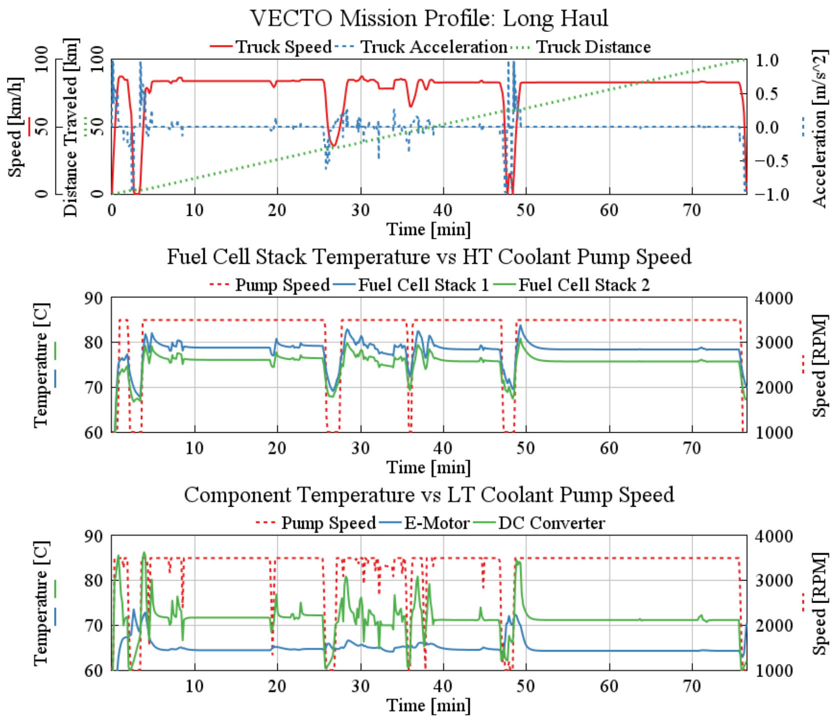

Figure 11: VECTO Mission Profile Long Haul Simulation Results

The simulation results of the VECTO mission profile regional delivery in Figure 12 show that even under more dynamic driving conditions, the designed cooling system with the optimized heat exchanger stack is capable of keeping the temperatures of the fuel cell powertrain in the desired temperature range.

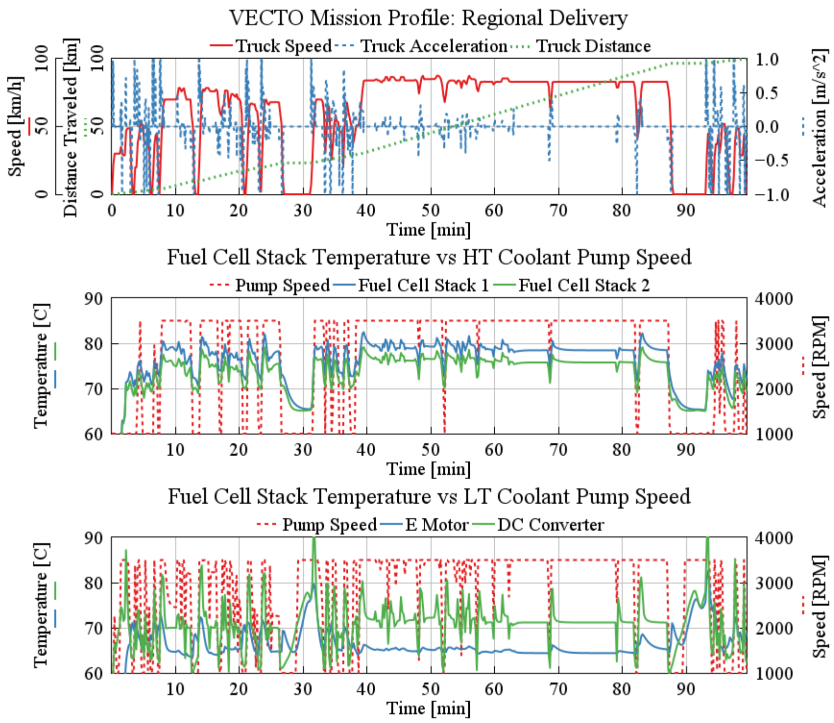

Figure 12: VECTO Mission Profile Regional Delivery Simulation Results

The simulation results of the real driving route over the Brenner Pass from Italy to Austria in Figure 13 show that the designed cooling system is capable of ensuring the thermal security of all fuel cell powertrain components at real driving scenarios.

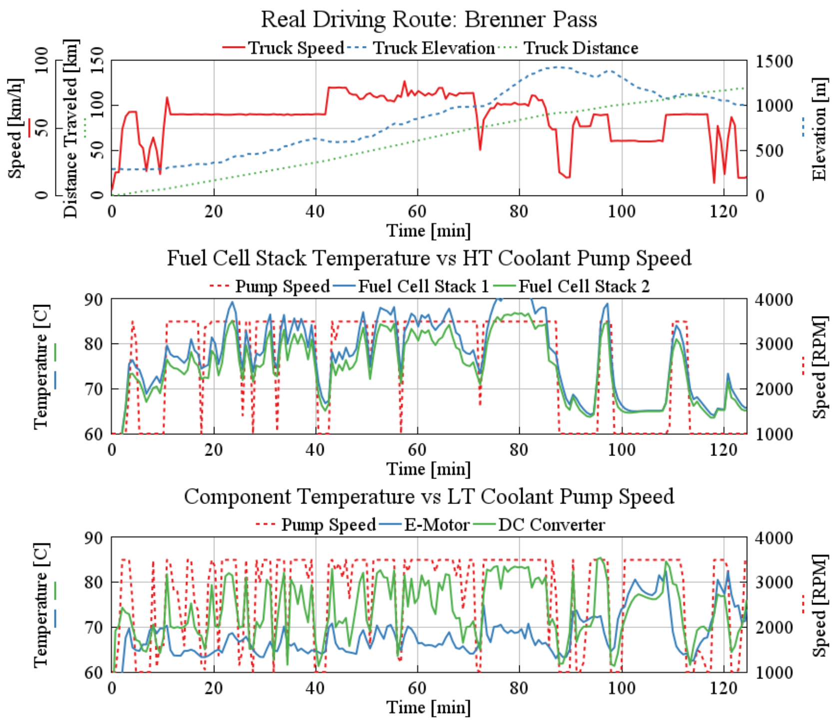

Figure 13: Real Driving Route Brenner Pass Simulation Results

At about 75 minutes of driving in the Brenner Pass scenario it can be observed that the fuel cell stack, that was observed to show overall higher outlet temperatures in the VECTO cycles, reaches an outlet temperature of 90 °C. While under the boundary conditions of this study it also shows that the cooling system is designed with narrow margins at high load high temperature conditions. Also we here we are demonstrating the advantages of the proposed holistic methodology. Following the finding from the Brenner Pass results the holistic system model can easily be used to test additional load cycles or to develop appropriate derating strategies of the powertrain.

4 Conclusion

We present a methodology to address the thermal management challenges of fuel cell based mobility platforms with holistic system simulation to design and optimize the cooling system and heat exchanger stack of a fuel cell truck using the simulation software GT-SUITE.

To overcome the challenge of the low temperature difference in the cooling system at hot ambient conditions the design and size of the LT and HT radiators are optimized with respect to the fuel cell stack and powertrain component temperatures to ensure thermal security of the fuel cell powertrain.

The VECTO mission profiles long haul and regional delivery and a real driving route over the Brenner Pass created with GT-RealDrive are used to verify the thermal security of the fuel cell powertrain over the complete operating range at dynamic loads.

For future studies, the holistic system simulation approach can be extended to additional areas like selection and optimization of other components of the fuel cell truck cooling system and its control logics.

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