Intelligent thermal management simulation of a fuel cell system

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ABSTRACT: Electric vehicles that use fuel cells to generate on-board electricity are considered the cornerstone of zero-carbon, zero-emission long-haul heavy-duty transportation. Besides the main energy source, the fuel cell, a fuel cell system is complemented by a thermal management system. A key function of the thermal management system is to ensure a safe and efficient operation. Insufficient thermal management at high fuel cell power levels requires a derating of the performance and thus to a drop in power output to avoid damages to the fuel cell stack. With fuel cells, the required cooling capacity is significantly higher than with combustion engine powertrains of the same power. This leads to a higher required cooling air flow and to higher pressure losses in the cooling module and engine compartment.

With this in mind, the paper uses a modular fuel cell electric vehicle model to couple the physical thermal models of the components such as radiators and fans to optimize the complete cooling system. Due to their specific performance characteristics, axial fans will possibly not be able to provide sufficient air flow and pressure rise. Hence, different fan designs (axial, combined axial/radial, etc.) will be compared and evaluated regarding their impact on energy consumption and fuel cell performance. A thermal management strategy is then developed to minimize performance degradation as well as energy and fuel consumption. The overall system performance is analyzed for an exemplary driving cycle.

KEY WORDS: EV and HV systems, fuel cell, thermal management control system, energy management,

1. INTRODUCTION

Fuel cells (FC) are widely regarded as one cornerstone in the decarbonization of commercial vehicles. They offer carbon- and emission-free mobility in combination with short refueling times and high range. Due to the large variety of application of commercial vehicles – from light commercial to heavy-duty and long haul – a wide range of necessary powertrain power is required. For early market competitiveness and to cope with the large power range, fuel cell systems are often designed in a modular fashion for cost reduction. Besides low system costs, the pressure on development times and effort is equally high, making an efficient development process inevitable.

Especially for heavy-duty long-haul vehicles such a development process must consider the thermal system of the fuel cell. For this application the fuel cell is usually operated at higher current density during the load cycle, compared to passenger cars. Since, the fuel cell's efficiency is dropping with increasing load, the cooling demand is increasing exponentially. This behavior in combination with the high-power demand during hill climb and limited radiator space leads to a derating of the fuel cell once a certain ambient temperature is exceeded.

To improve the thermal stability of the fuel cell system several strategies are elaborated within this paper. These strategies involve the improvement of the radiator's cooling capacity via different fan designs, optimized hybrid strategy as well as thermal strategy.

2. CHALLENGES OF THERMAL MANAGEMENT FOR FUEL CELL POWERTRAINS

Looking into the powertrain configurations of current heavy-duty trucks worldwide it can be seen that typical EU trucks are equipped with 300-370 kW Diesel engines. US trucks usually have higher power ratings of 320-400 kW. In China the power ranges from 200-300 kW. (1) Due to this variation in power rating, the strategy of most OEM and Tier 1 supplier is to supply modular stacks and systems with output powers ranging between 80 kW and 150 kW and using multiple units to meet the power requirements and achieve economy of scale. Furthermore, efforts are taken to standardize such modular fuel cell system within the

EU-funded project "StasHH" (2). For the current investigations a 40-ton truck for the European markets was selected with a fuel cell system net power of 300 kW, since it represents the most common vehicle and OEMs as Daimler Truck and Volvo, announced first fleet tests (3).

Challenge for fuel cell systems with such high power rating is the heat dissipation, especially at elevated ambient conditions. With PEM fuel cells usually operating at temperatures around 80 °C the temperature difference to the ambient is relatively low. Furthermore, the losses of the fuel cell stack are almost fully dissipated via the cooling system due to the very low exhaust gas enthalpy. To exemplify this challenge the waste heat calculation in a full load operation point is given in the following: Assuming a necessary stack power for the 300 kW net power output of 350 kW at 50% efficiency, temperature increase of 10 K over the stack, stoichiometry of 1.8, and specific heat capacity of humid air of 1.5 kJ kg^{-1} K^{-1} the heat dissipation into to coolant is 344.6 kW. An additional amount of 5.4 kW is bound in the exhaust gas. Decreasing the efficiency to 45%, the waste heat into the coolant increases to 421.8 kW. Since fuel cells degrade towards the end-of-life such an efficiency decrease must be considered during the design of the thermal system (4) .

Due to the above challenges, large surface area radiators and high-powered cooling fans are required. Furthermore, additional heat load must be accounted for if the same radiator is used for other components. Such components are the charge air cooler of the fuel cell system, battery system, power electronics and HVAC.

3. MODEL DESCRIPTION

Within this section the vehicle specification, powertrain model, thermal model, energy management and thermal model control strategy is presented.

3.1. Powertrain model

The scope of work for this study includes a longitudinal dynamics simulation of a fuel cell hybrid truck for the European market. Additional information on the used simulation model can be found in Zubel et al. (7). For the truck used in these studies, a fuel cell stack size of 349 kW gross power is selected. Considering the losses of the auxiliary consumers, the net power of the fuel cell system is approx. 300 kW. The performance of the fuel cell electric vehicle (FCEV) will be evaluated for the 'Brenner Pass' and 'VECTO' cycle. The considered vehicle specification are summarized in Table 1. The powertrain model includes a regression model for the fuel cell system, a transmission, DC/DC converter, a thermal model and map-based electric machine and battery. The regression model used in this paper calculates a cell voltage depending, among other parameters, on air stoichiometry, stack current, coolant inlet and coolant temperature difference over the stack. In combination with the thermal system, a direct influence of the coolant temperature on the cell voltage is given. Hence, a decrease of the cell voltage due to increased coolant inlet temperature is considered.

In addition, the modeling includes a hybrid control unit (HCU), a fuel cell control unit (FCCU), a battery management system (BMS) and a thermal management control (TMC). The TMC targets a thermal balance of the stack temperature under actual driving conditions.

Table 1: Vehicle specifications

Parameter	Specification	Unit
Max. vehicle weight w/o trailer	19.5	Tons
Max. vehicle weight w/ trailer	40	Tons
Fuel cell net power	300	kW
E-motor power	428	kW
Batter capacity	70	kWh
Rolling resistance coefficient	0.0055	-
Vehicle frontal area	9.38	m²
Air resistance factor	0.58	-
Aux. power	19	kW
Max. fan power	36	kW

3.2. Thermal model

The modeling of the thermal system is focused on the essential areas of the system. The low-temperature circuit, which is responsible for cooling the airflow and the power electronics, was not considered, as is not in focus of this work. Such a simplification is viable, since these components require different temperature levels and are usually cooled with a separate circuit.

The model of the thermal system therefore includes the essential components and parts of the fuel cell circuit: piping, coolant pump, the thermal mass of the fuel cell stack and the radiator module. The radiator module was modeled based on internal 3D data and then processed for the use in an 1D simulation environment. It includes the radiator, the radiator grille, the shroud, and a fan with a high-voltage drive motor. In the basic configuration of the system, an axial fan was used. All components were parameterized with data from an internal database to represent realistic components. This configuration of the simulation model ensures that the interaction between the fuel cell system and the thermal system can be represented with sufficient accuracy.

The whole model is designed in such a way that the individual components can be replaced for further optimizations of the system.

3.3. Controls

In the following the control strategies for the HCU and TMC including fuel cell system derating are briefly introduced.

Within the hybrid control unit five different driving states are defined. These driving states are explained in the following: 1. Battery electric driving; 2. Boosting; 3. Fuel cell (FC) driving and charging; 4. FC driving; 5. Recuperation. The hybrid state manager switches between these modes based on the driver's power demand and the battery state of charge (SOC). While driving, a SOC window between 50 % and 60 % is targeted to reserve enough battery capacity for recuperation and boosting. The upper and lower SOC limits depend on the battery type and are defined as 30 % as the lower limit and 80 % as the upper limit for the present study (7).

The control strategy for the thermal system was derived from the requirements of the fuel cell system. A value of 84 °C was defined as the maximum stack outlet coolant temperature. Above this temperature major damages of the fuel cell can occur. Especially, the stability of the membrane decreases drastically as temperatures increase beyond the given value. Therefore, it is important to avoid exceeding the maximum coolant temperature for longer periods of time. Another important criterion for the design of the control strategy was the limitation of the temperature difference across the fuel cell stack, which should be 7 K in the best case. These criteria are met by selectively controlling the coolant pump and the fan. In a first step, the coolant flow rate is increased. The focus here is on regulating the correct temperature difference over the fuel cell stack with high accuracy. The maximum coolant flow rate is set at 800 L/min. The additional actuation of the fan is used to maintain the maximum coolant temperature.

Depending on the required load profile it is not always possible to supply sufficient cooling to the fuel cell stack, especially at elevated ambient temperatures. This necessitates the implementation of a derating strategy to prevent the limit temperature from being exceeded over a longer period. The maximum power delivery of the fuel cell system is limited by a comparison with the heat energy that can be dissipated via the cooling module in the particular moment. This requires a coupling of the thermal strategy with the hybrid strategy. The requested power of the fuel cell is reduced to not exceed the maximum waste heat that can be dissipated. Therefore, the battery must supplement the missing electrical power to maintain a proper continuation of the driving scenario. If the SOC of the battery is not sufficient the traction power and thus the vehicle velocity has to be decreased to maintain secure operation conditions.

The described control strategies are used as a baseline for the evaluations presented in this paper. In the further course of this work the system and the strategy will be adapted to improve the energy efficiency.

4. Results

The goal of this contribution is to show different approaches to optimize a fuel cell system and its control strategy to improve energy efficiency and performance. For this purpose, different investigations will exemplarily be presented in this paper. For the system optimization an improved cooling fan design is considered. After that the updated interaction between an optimized thermal management control strategy and hybrid control strategy is examined. A specific reference case is defined in the following to deliver a baseline.

4.1. Reference case

The impact of the thermal strategy on the fuel cell system is evaluated based on selected cycles. With the introduction of the Vehicle Energy Consumption calculation TOol (VECTO) for heavy duty vehicles the European Commission launched five different mission profiles for trucks to reflect the CO_2 emissions and fuel consumption of the European fleet. The VECTO long-haul cycle is a representative cycle for long-haul, highway-dominated driving transportation. (8) (9) The Brenner Pass is one of the most important transit routes through the Alps. For the thermal system of the fuel cell hybrid vehicle, the climb of approx. 750 m of the first part represents a particular challenge, especially regarding the high power demand of fuel cell system.

The following simulation results consider a fuel cell hybrid truck in fully loaded condition at 25 °C ambient temperature.

Fig. 1 shows the performance of the fuel cell during the Brenner Pass. Fig. 1a illustrates the driving and altitude profile over distance. In addition, Fig. 1b gives an overview of the delivered stack and system power as well as the derating power of the fuel cell stack and fan power. The regulation of the fuel cell power limitation depends on the coolant temperature, which is shown in Fig. 1c. When the coolant temperature of 84 °C is exceeded at the radiator inlet, the power limitation is activated. The amount of power reduction results from the balance of the waste heat of the fuel cell, the cooling power of the fan and the convective heat removal by the vehicle speed.

During the hill climb in the first part of Brenner Pass, it can be observed that the fuel cell is operated at full load. The resulting system power is the difference in stack power to Balance-of-Plant (BoP) and thermal system power demands. At peak, 40 kW of power is required for the thermal system (fan and cooling pump). Despite the max. fan power, a power limitation of up to 14 kW is required to maintain the temperature conditions of the thermal system. The resulting power limitation due to the thermal system is compensated by the battery to minimize performance losses in the speed profile. Negative power demand at the wheel dominates the hill descent and results in a reduced fuel cell operation. A briefly increased power limitation of up to 60 kW can be explained by a delay of the interaction of the different controls and the inertia of fan operation.

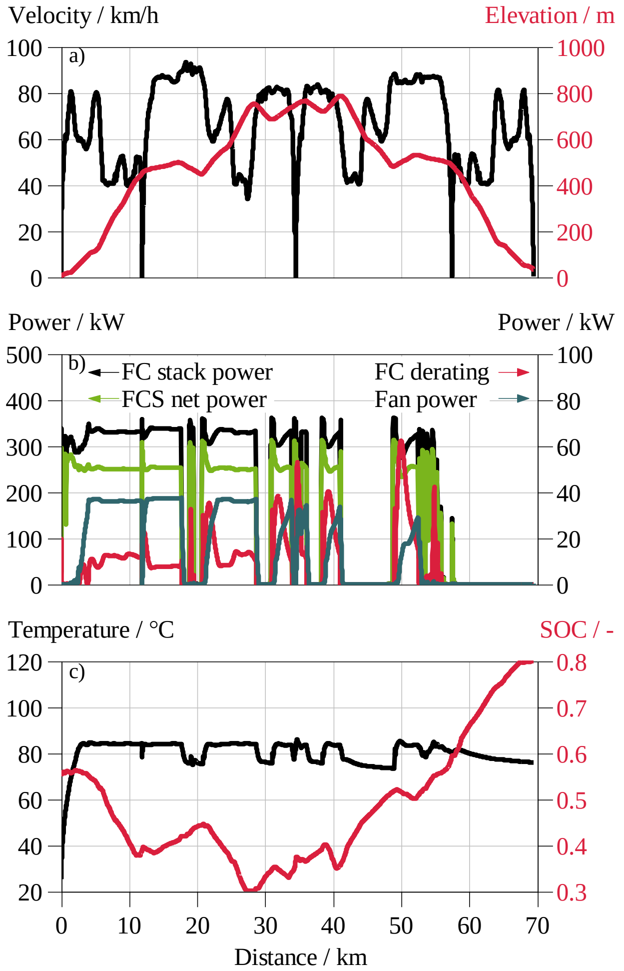

Fig. 1 ‚Brenner Pass‘ vehicle simulation result with reference fan.

In contrast, Fig. 2 shows the fuel cell performance in the VECTO long haul cycle. The cycle is dominated by constant speeds at 84 km/h and moderate road grades. Single rapid speed changes in combination with positive road grades lead to high power demands and thus to potential power limitations. Compared to the Brenner Pass, the fuel cell is predominantly operated in the range between 100-200 kW. Part load operation of fuel cells is characterized by higher system efficiency and reduced fuel consumption compared to full load operation. This part load operation leads to lower heat dissipation of the fuel cell stack which reduces the need for power limitation of the fuel cell and cooling demand. In peak, a power limitation of up to 45 kW can be found which can also be explained by the inertia of fan operation. Performance losses due to a reduced total system power output are not given.

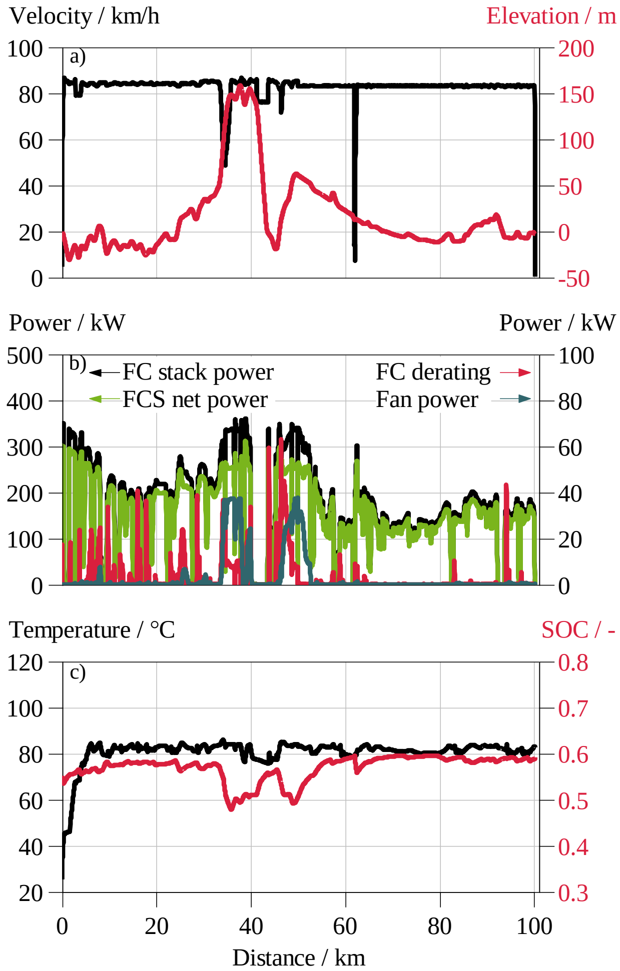

Fig. 2 ‚VECTO‘ long haul vehicle simulation result with reference fan.

The ambient temperature has a non-negligible influence on cooling power performance. Fig. 3 plots the fuel consumption of the fuel cell versus ambient temperature. As ambient temperature increases, the demand on the thermal system and the need for power limitation increases. During the Brenner Pass, the power limitation increases during the uphill climb. The increase in FC power limitation results in reduced stack power. This shift in load point of the fuel cell leads to higher stack efficiencies and reduced fuel consumption. While a decreasing trend in fuel consumption is evident for the Brenner Pass with increasing ambient temperature, the fuel consumption increases in the case of the VECTO long haul cycle. This effect is driven by the load point shift towards higher fuel cell stack power caused by higher cooling power demand. The shown fuel reduction for the Brenner Pass goes hand in hand with a disadvantage of vehicle performance. As Fig. 1b shows the fan is operating on maximum power during the hill climb while a slight FC derating is active. With increasing ambient temperature one can realize that the FC derating increases which leads to a reduction of the available system power output, which adversely affects the vehicle performance. The lower diagram of Fig. 3 shows the simulated time the vehicle needs to complete the cycle as an indicator for the vehicle performance. It can be observed that the simulated cycle time increases sharply in the case of the Brenner Pass, while the simulated cycle time increases only slightly for the VECTO long haul cycle.

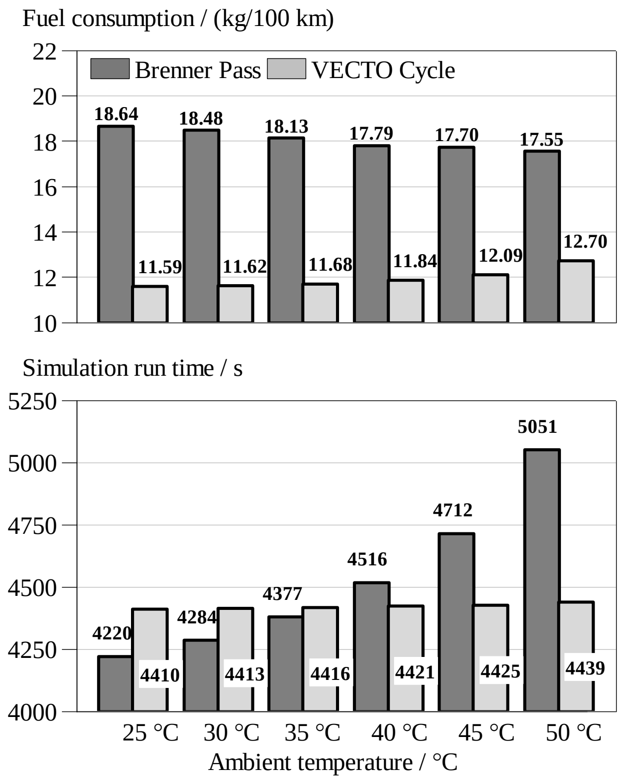

Fig 3 Average fuel consumption (top diagram) and simulated cycle time (upper diagram) at varying ambient temperature for the Brenner Pass and VECTO long haul cycle.

4.2. Improved fan design

To optimize the thermal system, the use of an alternative fan concept is to be investigated. By changing from an axial fan in the basic configuration to a radial fan in the optimized system assembly, an increase in fan efficiency and the achievable cooling capacities is expected. A comparison of the maximum cooling performance at 80 km/h using both fans as a function of electrical power demand (Fig. 4) clearly shows that the optimized fan concept is promising for additional energy savings.

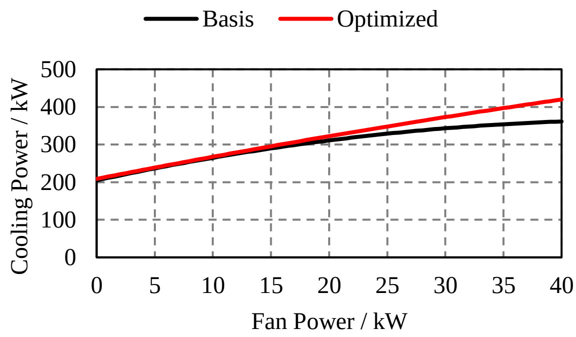

Fig. 4 Cooling performance over fan power at 80 km/h

The comparison of the selected fans in Fig. 4 shows that the optimized fan generates an equal or higher cooling power at a given fan power compared to the base design at a vehicle speed of 80 km/h. Which means that for the same requested stack power, the power demand of the thermal system (fan and coolant pump) is lower for the optimized case and results in a higher system power output.

Fig. 5 shows simulation results of the optimized fan design during the previously discussed drive cycles. Shown are vehicle speed (Fig. 5a), fuel cell net output power and EM power (Fig. 5b), and the battery SOC level (Fig. 5c) for the base and optimized fan design during an uphill drive section of the Brenner Pass.

While the requested powertrain power is the same for both cases the system net output power of the optimized design is approximately 9 kW higher, see Fig. 5b.

The surplus of the system net output power is stored in the battery to either support the powertrain with the battery at high power peaks or to drive the vehicle battery electric. As one can see the additional fuel cell net power output leads to a performance advantage due to a power reserve on the battery side, see Fig. 5c from time 1700 s and following. In total a fuel saving of 0.2 kg/100 km and performance advantage (13 sec. reduced simulated cycle time) can be realized using the optimized fan design during the Brenner Pass.

It should be mentioned that the effects are higher for driving scenarios with high load requirements on the stack and thermal system compared to driving scenarios with low load requirements such as the VECTO long haul cycle. As shown in Fig. 6 the fuel saving potential is less compared to the Brenner Pass.

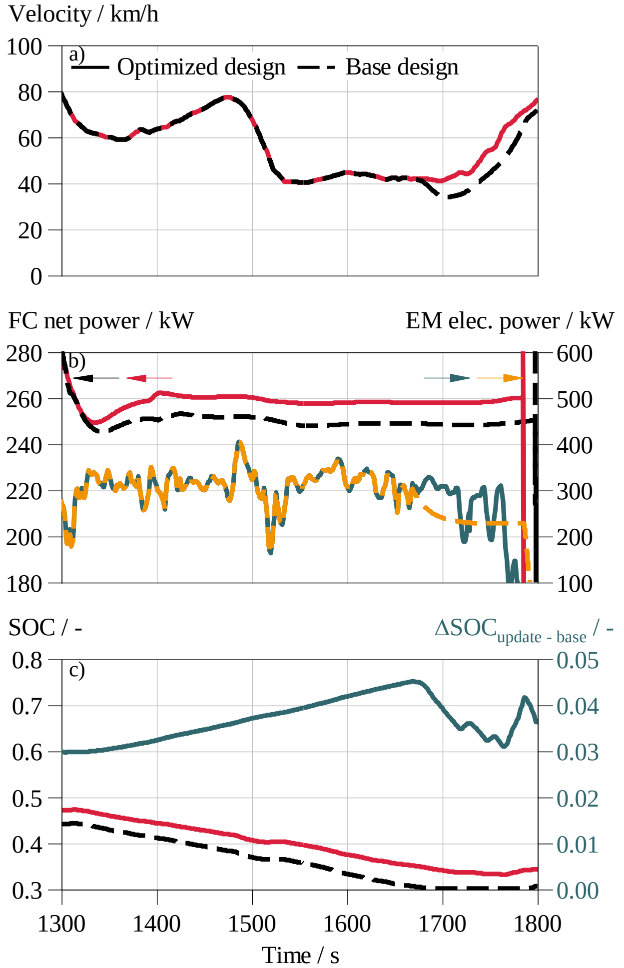

Fig. 5 Extract from the simulation results: Base fan design vs updated fan design at Brenner Pass.

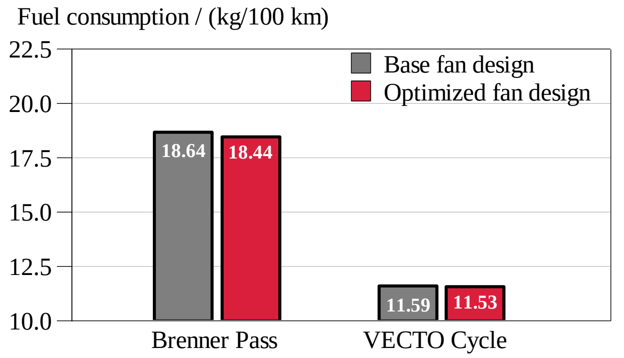

Fig. 6 Fuel consumption comparison of base (grey bar) and optimized (red bar) fan design in Brenner Pass and VECTO long haul cycle.

4.3. Optimized thermal strategy

After the hardware improvements, the operating strategy of the thermal system is optimized. For this optimization a cost function is utilized. This function weights the powertrain efficiency against the associated performance gap, depending on the battery SOC, ambient temperature, and vehicle speed. The strategy exploits the efficiency characteristics of the fuel cell where the efficiency increases with decreasing power output. To realize the strategy, fan speed-, vehicle velocity-, and ambient temperature-depended maps for the maximum heat dissipation of the radiator are used together with an efficiency map of the fuel cell system. With these maps the powertrain efficiency and associated net power deficit can be calculated and assessed by the cost function. The cost function in conjunction with the battery SOC defines the ideal fuel cell system power. The resulting gap in propulsion power will be filled by the battery.

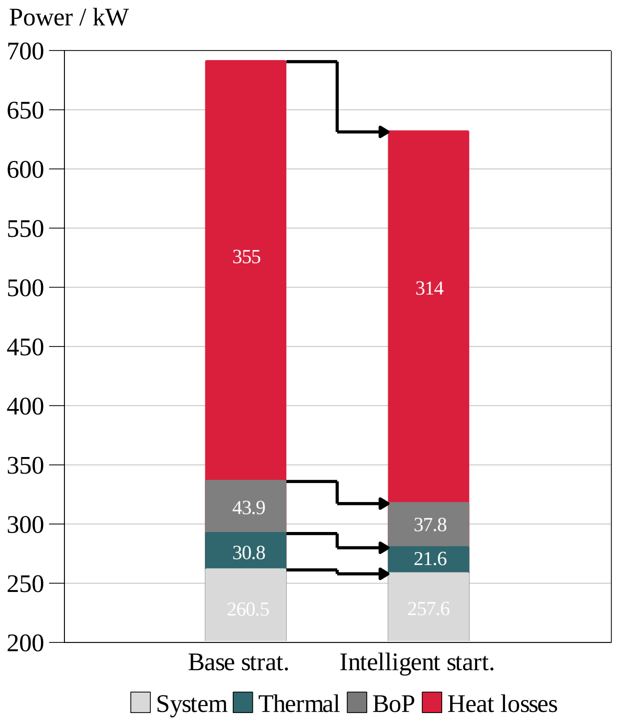

Fig. 7 Exemplary power distribution for base and intelligent thermal management strategy

Fig. 7 shows a case study of the power distribution for the base and intelligent thermal management strategy. As mentioned, the intelligent strategy uses, among other parameters, information on powertrain efficiency and stack performance to calculate the ideal net system power using a cost function. The intelligent thermal management strategy applies a derating of 18 kW to the fuel cell stack power, which saves in total 15 kW for BoP components and fan. Due to this compensation a nearly equal net system power output for both strategies are available. This load point shift translates into an increase in fuel cell efficiency as indicated by the more than 40 kW reduced heat losses in Fig. 7. The resulting savings in fan and BOP power requirements result in a comparatively small system power drop.

Fig. 8 shows the fuel consumption and simulated cycle duration for both cycles at 25 and 50°C ambient temperature for the base and intelligent thermal strategy. Thus, one can see that at 25 °C ambient temperature during the Brenner Pass 6.9 % (1.27 kg/100 km) fuel can be saved using the intelligent thermal strategy while the travel time increases only by 27 s. Under increased ambient temperatures (50 °C), a saving potential of 7.7 % (1.32 kg/100 km) is possible with an increase in travel time of 5 min. Even with moderate load requirements as in the VECTO long haul cycle, the intelligent thermal strategy shows savings potential of 0.2 kg/100 km at 25 °C and 0.99 kg/100 km at elevated ambient temperature (50 °C) at an increased driving time of 1 min.

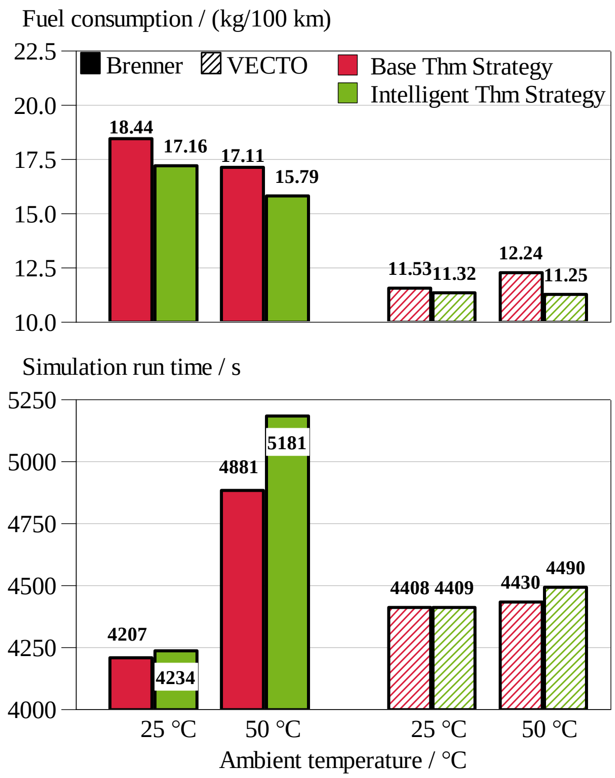

Fig. 8 Fuel consumption of base thermal management strategy (red) vs intelligent strategy (green) using optimized fan design in Brenner Pass at 25 and 50 °C ambient temperature.

5. CONCULUSION

Within the present study a numerical performance investigation of a fuel cell electric heavy-duty truck, considering the thermal system was presented. The powertrain- and thermal model as well as the controls for energy management, thermal management, and derating were introduced. Finally, a thermal strategy for the on-board optimization of hydrogen consumption, accounting for the ambient conditions and battery SOC, was presented.

In a reference scenario without an intelligent thermal strategy, the truck completed the VECTO long haul and Brenner Pass with a simulated hydrogen consumption of 11.59 kg/100 km and 18.64 kg/100 km respectively at an ambient temperature of 25 °C.

With increasing ambient temperatures, the fuel consumption increases for the VECTO long haul cycle due to the higher fan power requirement. In case of the Brenner Pass the opposite trend for the fuel consumption is noticeable. The reduction of fuel consumption is a result of increasing fuel cell derating requirement with increasing ambient temperature. However, this increase comes with a penalty in vehicle performance since the powertrain is no longer capable of supplying the required power demand.

With the intelligent thermal management strategy, the ambient temperature until derating cannot be changed since the physical limitations of the radiator cannot be overcome due to the long duration of high power demand. However, the fuel consumption for the Brenner Pass could be reduced by 1.27 kg/100 km while the cycle duration only increased by 27 s. Within the VECTO long haul cycle the fuel consumption could be decreased by 1.8 % with the intelligent thermal strategy.

The reduction in hydrogen consumption is mainly due to the stronger derating of the fuel cell, leading to an efficiency increase of the stack and therefore lower stack and cooling fan power requirement. Through this optimization the power available for vehicle propulsion is only slightly reduced, while the powertrain efficiency is drastically increased. This behavior is most pronounced during phases of high power demand and high ambient temperatures.

For future investigations predictive control strategies shall be considered for the hybrid control and the thermal system control. By doing so the future system states and the characteristics of the route can be incorporated to further optimize and adapt the controls of the overall system. Additional energy savings are expected and could contribute to a better interaction between the hybrid control unit and the thermal management system.

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