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Journal of Power Sources 145 (2005) 298–306
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Effects of ambient conditions on fuel cell vehicle performance

K. Haraldsson*, P. Alvfors**

KTH Chemical Engineering and Technology, Div. of Energy Processes, Royal Institute of Technology, Stockholm, Sweden

Accepted 22 December 2004
Available online 3 June 2005

Abstract

Ambient conditions have considerable impact on the performance of fuel cell hybrid vehicles. Here, the vehicle fuel consumption, the air compressor power demand, the water management system and the heat loads of a fuel cell hybrid sport utility vehicle (SUV) were studied. The simulation results show that the vehicle fuel consumption increases with 10% when the altitude increases from 0 m up to 3000 m to 4.1 L gasoline equivalents/100 km over the New European Drive Cycle (NEDC). The increase is 19% on the more power demanding highway US06 cycle. The air compressor is the major contributor to this fuel consumption increase. Its load-following strategy makes its power demand increase with increasing altitude. Almost 40% of the net power output of the fuel cell system is consumed by the air compressor at the altitude of 3000 m with this load-following strategy and is thus more apparent in the high-power US06 cycle.

Changes in ambient air temperature and relative humidity effect on the fuel cell system performance in terms of the water management rather in vehicle fuel consumption. Ambient air temperature and relative humidity have some impact on the vehicle performance mostly seen in the heat and water management of the fuel cell system. While the heat loads of the fuel cell system components vary significantly with increasing ambient temperature, the relative humidity did not have a great impact on the water balance. Overall, dimensioning the compressor and other system components to meet the fuel cell system requirements at the minimum and maximum expected ambient temperatures, in this case 5 and 40 °C, and high altitude, while simultaneously choosing a correct control strategy are important parameters for efficient vehicle power train management.

Keywords: Proton exchange membrane (PEM) fuel cell system; Fuel cell hybrid vehicle; Performance; Ambient conditions

1. Introduction

Low-temperature proton exchange membrane (PEM) fuel cells are considered for power generation for electric vehicle applications. Hydrogen-fuelled fuel cell vehicles provide higher efficiency and extended operating time than battery-driven vehicles. These vehicles also feature higher efficiency than corresponding conventional vehicles especially at the part-load range of the power–efficiency map as well as considerably reduced tail–pipe emissions. However, since the fuel cell technology is still under development, a hybrid fuel cell vehicle approach, i.e., including an energy buffer such as a battery or super capacitor, to power-assist and/or recover braking energy, may be the most viable approach to implement fuel cell technology in vehicular applications in the near-term future.

The criteria on performance of a conventional vehicle also apply for a fuel cell hybrid vehicle. Widely varying ambient operation conditions including temperature, altitude and road grades have significant impact on fuel cell hybrid vehicle performance. Good control strategy, i.e., power balancing of the fuel cell and the energy buffer systems, is essential to meet the power demand of the duty cycles. In addition, proper design and dimensioning of the heat and water management of the fuel cell system is critical for the overall performance.

Extreme ambient conditions such as high altitude driving entail low ambient air temperature, pressure and density (see Fig. 1). For instance, the ambient air density is reduced by

* Corresponding author.
** Co-corresponding author. Tel.: +46 8 790 6526.
E-mail addresses: kahn@kth.se (K. Haraldsson), alvfors@kth.se (P. Alvfors).

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doi:10.1016/j.jpowsour.2004.12.080

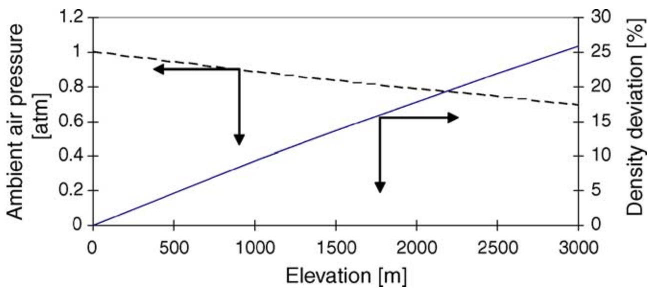

Fig. 1. The effect of altitude on ambient air pressure and density. The density is shown as deviation from the sea-level value of the density. Based on [3].

more than 10% at an altitude of 1000 m or by 25% at an altitude of 3000 m. The decrease in temperature, pressure and hence density impact negatively the fuel cell system performance. As a result, the power demand of the compressor and other auxiliary system components increases. Furthermore, as the fuel cell stack will operate less efficiently, producing more waste heat, the ability of the system to reject heat is affected and needs to be considered when dimensioning the thermal management system components.

Studies on effects of altitude on PEM fuel cell systems, mainly for auxiliary power units in high-altitude aircrafts, have been reported by several authors, e.g., [1,2]. For instance, NASA has studied unmanned aircrafts such as Helios and Pathfinder tested at altitudes well over 15,000 m, and recently, Boeing and Cessna have started tests of PEM fuel cell stacks as replacement of batteries in conventional aircraft with passenger capacity.

Due to lack of available experimental data of altitude effects on PEM fuel cell systems, detailed modelling is required to estimate the fuel cell system power demand, and dimension the system components accordingly, as a function of ambient conditions, duty cycle and control strategy (see Fig. 2). In this study, key performance characteristics of hydrogen-fuelled fuel cell hybrid vehicle operation at varying ambient conditions are demonstrated.

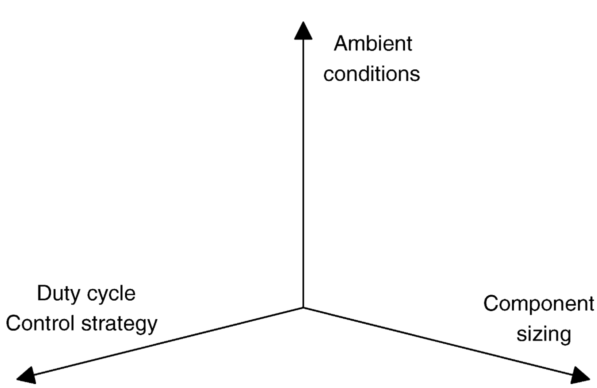

Fig. 2. Parameters impacting on fuel cell system component sizing; ambient conditions and duty cycle and control strategy.

2. Fuel cell vehicle description

A fuel cell hybrid mid-size sport utility vehicle was defined in the commercially available vehicle simulation software, ADVISOR, developed by National Renewable Energy. Laboratory, U.S., and provided by AVL [4]. This study is partially based on previous ADVISOR studies, e.g., [5–8]. Some of the assumptions on the fuel cell hybrid vehicle and power train given in Table 1 have also been used in previous studies. In the control scheme, it is assumed that the fuel cell system remains on at all times during the drive cycle unless the ignition key is turned off. This is done to provide a reliable operation of the fuel cell hybrid vehicle of today as start-ups and shutdowns of the fuel cell system may be coupled with some concerns. The energy buffer, in this case battery modules, is used for power-assist and regenerative braking energy recovery during duty cycles.

A hydrogen-fuelled PEM fuel cell system model as shown in Fig. 3 and Table 2 is used in the fuel cell hybrid SUV. The fuel cell system model consists of three major sub-systems: air and fuel supply, fuel cell stack and the coolant loop, and the humidification and water recovery system.

A model of a twin-screw air compressor is used in the air supply sub-system. The compressor is assumed to be fuel cell system load-following, i.e., the pressure output of the compressor increases with increasing fuel cell system load to provide the desired operation pressure. The operation range

Table 1
Vehicle and powertrain component assumptions

Parameters [units]	Sport utility vehicle
Fuel cell hybrid vehicle glider mass (no powertrain) [kg]	1202
Fuel cell hybrid vehicle mass (with powertrain) [kg]	1825
Frontal area [m^2]	2.66
Coefficient of aerodynamic drag [-]	0.44
Powertrain	
Motor/controller [kW]	117 (AC induction motor/inverter)
Fuel cell system [kW]	50
Energy buffer system [Ah]	12 (Li-ion battery pack)

Table 2
Fuel cell system assumptions

Parameters [units]	Value
Fuel cell stack	
Fuel cell area [cm^2]	678
Number of cells in stack [-]	210
Minimum cell voltage [V]	0.6
Stoichiometric coefficient (air)	2.5
Fuel cell system	
Net power output [kW]	50
System efficiency at rated power [%]	35
Peak system efficiency [%]	61

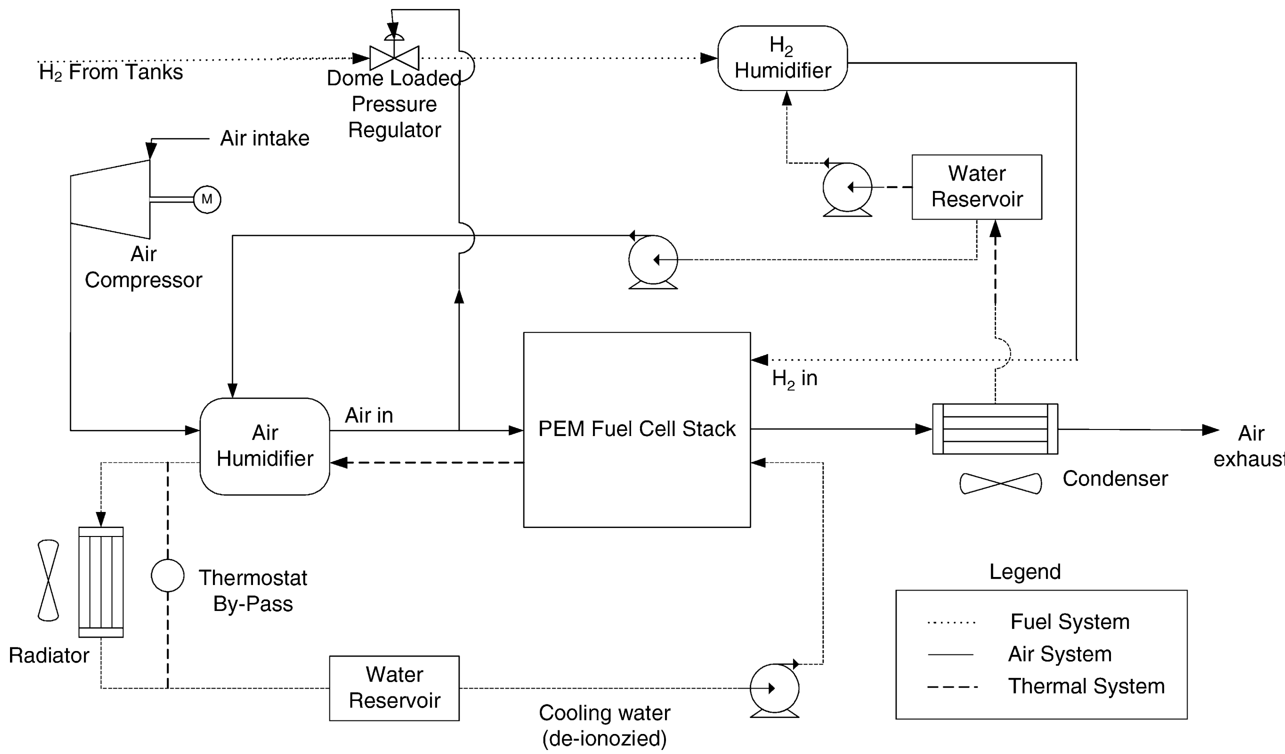

Fig. 3. Schematic of the ADVISOR fuel cell system model [7].

of the compressor is also dependent on parameters such as the duty cycle and control strategy.

The inlet gases are humidified in separate humidifiers. The exhaust is cooled in the condenser where part of its water content is condensed and recovered for recycling in the humidification process. The water reservoirs, humidifiers and condenser in Fig. 3 are used to maintain the water balance of the fuel cell system. The water balance is the difference between the water needed to humidify the inlet flows to the fuel cell stack and the part of the exhaust water that can be recovered in the condenser. To facilitate a good operation with few or no stops for refilling of water reservoirs for the water balance, it is desired that a maximum amount of water be recovered within the system.

The performance of the fuel cell system components is modelled, and for many of the components also controlled, to show similar characteristics as a real automotive fuel cell system. For instance, the heat transfer rates of both the condenser in the water balance loop and the radiator of the cooling system are dependent on vehicle speed, frontal area and ambient conditions. In addition, similar to conventional automotive propulsion design, the radiator is thermostatically controlled and is by-passed during cold starts until the fuel cell stack reaches its operating temperature.

The duty cycles used in the study are:

- NEDC—the New European Drive Cycle, which represents urban stop-and-go driving and has low maximum acceleration (1.06 $m\,s^{-2}$ PP).
- US06—a high-speed and high-acceleration (maximum acceleration is 3.76 $m\,s^{-2}$ PP) driving profile (to be a part of the U.S. EPA Supplemental Federal Test Procedure).

The duty cycles were used for simulations at constant altitude, from sea level up to 3000 m (the latter elevation corresponding to an average altitude for mountainous driving). In order to provide comparable results, all duty cycle results are presented as “state of charge (SOC) balanced”, i.e., there is only a minor difference between the SOC at the cycle start and the SOC at the cycle end. Cold and warm start-ups were also included in the simulations. “Warm start” means that the vehicle is warm at the beginning of the duty cycle. Normal ambient conditions for the fuel cell hybrid vehicle are here set to ambient air temperature and relative humidity of 20 °C and 75%, respectively, and at sea level (0 m).

3. Results

The fuel cell system model variables are treated as constants throughout the simulations. Only the ambient conditions were varied. Local weather and wind conditions were neglected. The results are divided into two parts. In the first part, altitude effects on the fuel cell hybrid vehicle are provided at constant ambient air relative humidity (RH) of 75%. The ambient air, pressure and density vary according to the altitude. This is of course an approximation of reality where the relative humidity changes with altitude as the temperature and pressure change. However, in this case, the impact of other ambient conditions such as temperature and pressure as functions of altitude was the focus. All results provided in this part are at warm starts. The second part incorporates results on sea level (0 m) with varying ambient air temperature and relative humidity (RH 30 and 75%). In addition, cold and warm start effects on system performance are provided in the second part.

3.1. Part I

3.1.1. Fuel consumption

As shown in Fig. 4, the vehicle fuel consumption is affected by the duty cycle elevation and increases with increasing altitude. The impact of altitude is highest on the high-power duty cycle US06. As the elevation increases from sea level up to 3000 m, the fuel economy is reduced with 19% on the power demanding highway cycle, the US06, for the SUV, whereas the fuel economy drops with 10% on the urban NEDC. This reduction in fuel economy is mostly contributed by the air compressor. The power demand of the air compressor increases with reducing ambient pressure as a result of increasing altitude.

The results also need to be seen in terms of not only compressor power demands but also vehicle speeds. The difference between the NEDC and US06 cycle is related to the different vehicle speeds and altitude. The heat transfer in the condenser and radiator is dependent on vehicle speed and ambient conditions. The vehicle speed is lower in the NEDC cycle than in the US06 cycle, thus more heat is rejected in the US06 cycle due to higher speed. Furthermore, as the ambient air density is lower at higher altitude, the vehicle has a lower aerodynamic resistance. All these parameters factor in on the vehicle fuel consumption results.

Over the NEDC and at sea level, the fuel cell hybrid SUV has an average fuel consumption of 4.1 L gasoline equivalents (gas equiv.)/100 km. In comparison, an actual fuel cell hybrid vehicle of similar weight, on a Volkwagen Bora (known in the U.S. as Jetta) platform, the fuel consumption is significantly higher, 34%, or 6.2 L gas equiv./100 km [9]. The difference in fuel consumption may be due to several reasons. Firstly, the Volkswagen vehicle is about 10% heavier than the simulated SUV and will therefore have higher fuel consumption due to the higher weight. Secondly, the different design and efficiency of fuel cell system components and power balancing of the fuel cell and energy storage device also contribute to the effect on the overall fuel consumption. Thirdly, the power train in the Volkswagen Bora uses a smaller AC motor size (75 kW peak) and an energy storage device consisting of 360 W h super capacitors, which is a significant smaller storage capacity than the SUV battery pack.

The net fuel cell system efficiency of the SUV as function of net fuel cell system power output over the US06 cycle at different elevations is shown in Fig. 5. The decreasing trend in system efficiency with increasing altitude is steady for the lower net system power outputs. It becomes increas-

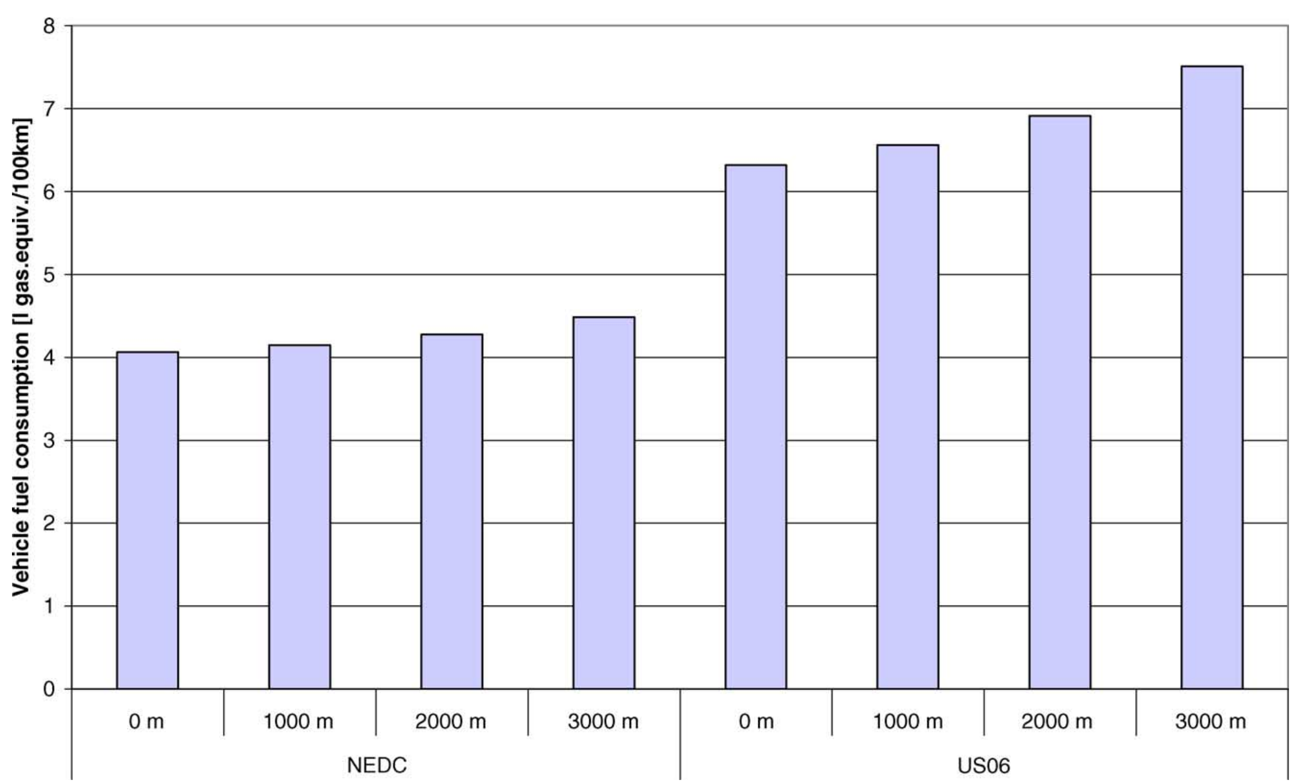

Fig. 4. The vehicle fuel consumption for the SUV at different elevation over the NEDC and US06 cycle.

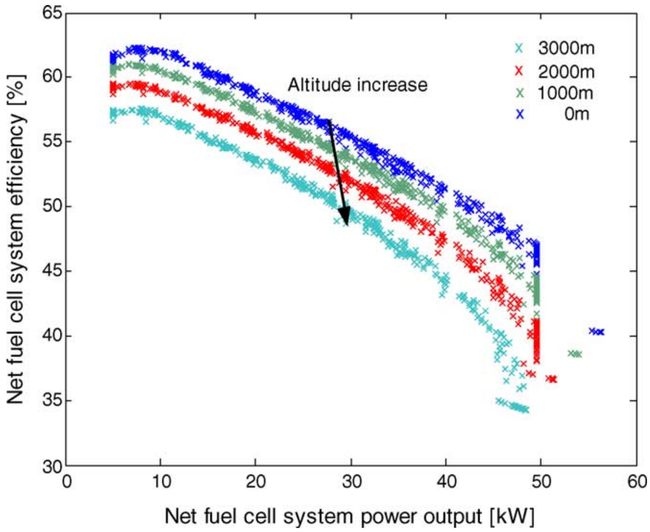

Fig. 5. The altitude impact on the net fuel cell system efficiency over the US06 cycle.

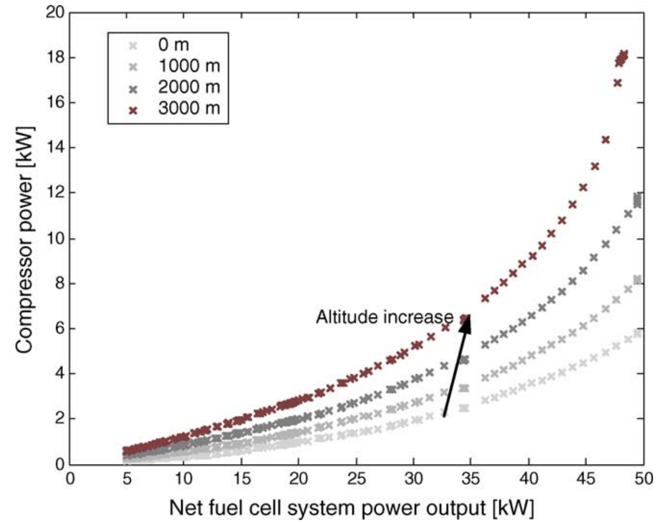

Fig. 7. The compressor power demand as a function of the fuel cell system net power output at different altitude.

ingly more difficult for the fuel cell system to achieve the high-power demands of the duty cycle at higher elevation and the system efficiency shows therefore a larger reduction. The outliers at each elevation level in the right-hand corner in Fig. 5 are power outbursts at high-speed points during the duty cycle. At increasing altitude, the fuel cell system fails to achieve these power peaks. As a result, the system is only able to provide lower power output at significant lower system efficiency.

3.1.2. Air supply system

The air compressor is the major parasitic system component in this fuel cell system. The air compressor is a twin-screw compressor, which is able to operate at multiple pressure ratios. However, this ability comes at the expense of energy efficiency. Fig. 6 shows the pressure ratio

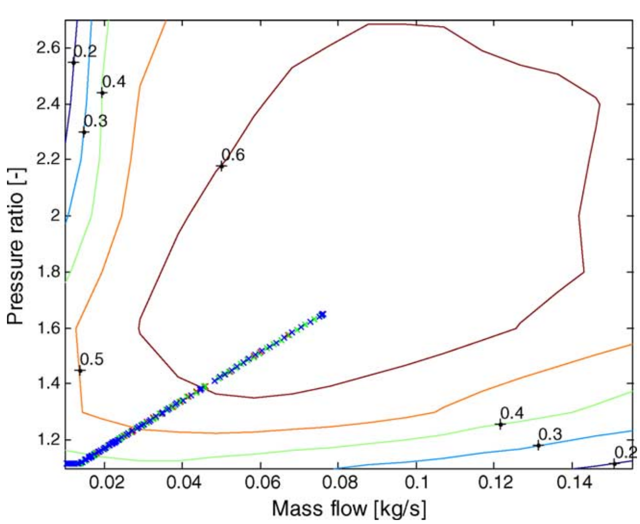

Fig. 6. Compressor pressure ratio, adiabatic efficiency and mass flow over the NEDC.

and the adiabatic efficiency of the compressor as a function of mass flow over the NEDC. Added in the figures is the duty cycle mass flow demand imposed on the fuel cell system. As seen in the figure, the urban duty cycle profile with its many stop-and-go situations, and the compressor control strategy, force the compressor to operate at low-efficiency regions.

The altitude impact can also be seen in the power demand of the compressor (see Fig. 7). The operating pressure strategy of the fuel cell system was as previously mentioned modelled to be load-following. Because of the load-following operating pressure strategy of the fuel cell system, the air mass flow and pressure ratio increases linearly with increasing power demand at constant stoichiometric flow. To provide the desired pressure ratio, the compressor workload is substantially increased, as the ambient pressure decreases at elevated altitudes. The difference in power demand from sea level up to 3000 m was 16%. The compressor power demand at 3000 m is as high as 40% of the fuel cell stack power output.

3.1.3. Heat loads

The heat distribution of the fuel cell system at different altitudes over the NEDC is shown in Fig. 8. In this urban cycle, the fuel cell stack reaches its maximum heat production level, about 73 kW (thermal), at 3000 m. The fuel cell stack operates rather efficiently at lower elevations and does not produce much waste heat to be used within the system and the radiator is therefore by-passed initially. This radiator starts to reject heat as the elevation increases to 2000 m when the fuel cell stack operates less efficiently and hence produces more waste heat. In parallel, at increasing altitude, the heat to be rejected from the condenser is reduced, providing more heat to the radiator.

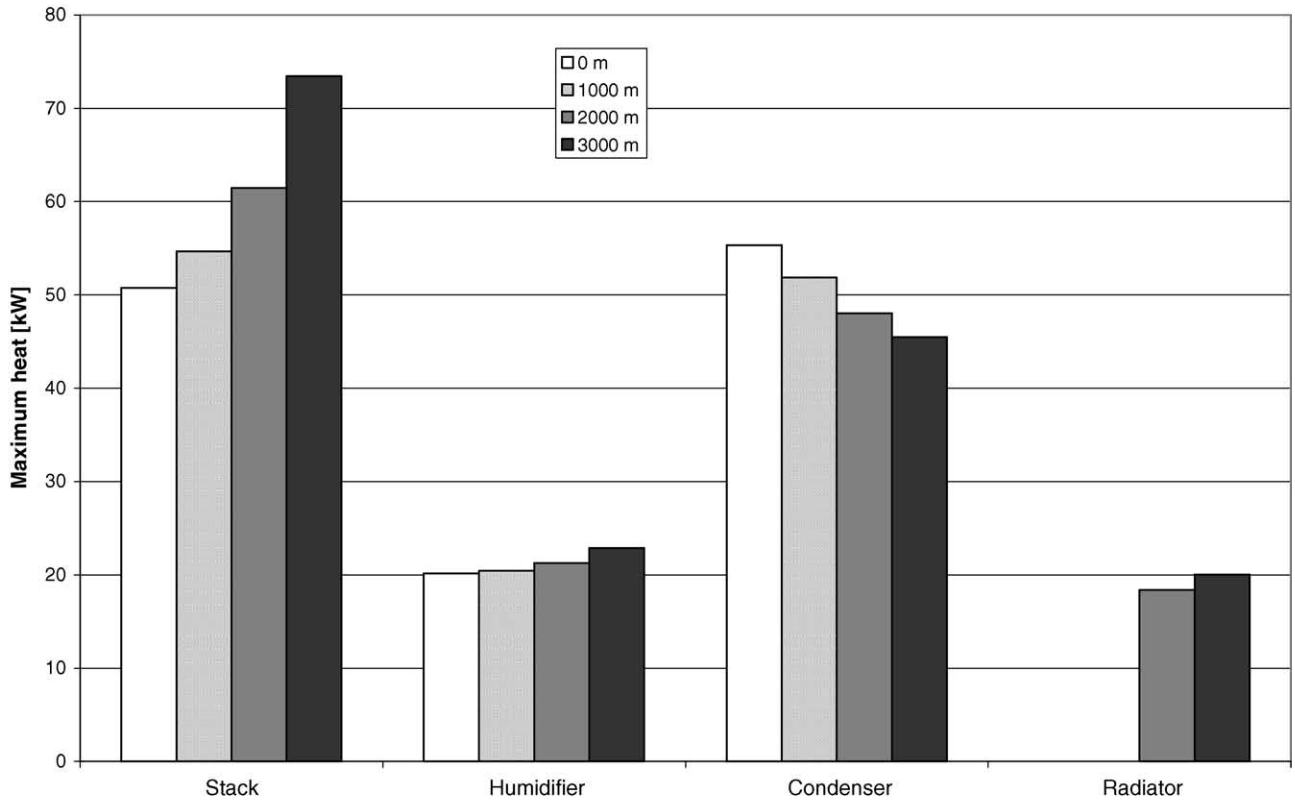

Fig. 8. Heat load distribution (maximum values) at different altitudes over the NEDC.

3.2. Part II

3.2.1. Water balance

The water management of the fuel cell system is closely linked to heat management. The water management during the duty cycle NEDC is shown in Fig. 9. The water reservoir capacity in this case was about 4 L of water. It was assumed that the water reservoir was at 50% of its capacity at the beginning of the duty cycle. As long as the resulting water balance of the system is between 50 and 75% of the water reservoir capacity, the condenser fan is on to facilitate heat rejection and water condensation. The water recovered from the condenser eventually filled up the water reservoir tank to about 80% of its capacity at the end of the duty cycle. Some of the water in the stack, i.e., the water from the humidification and water produced in the stack, is condensed within the stack and is not available for the water loop. In the mid-diagram of Fig. 9, the water available in the fuel cell stack and the water recovered in the condenser are shown.

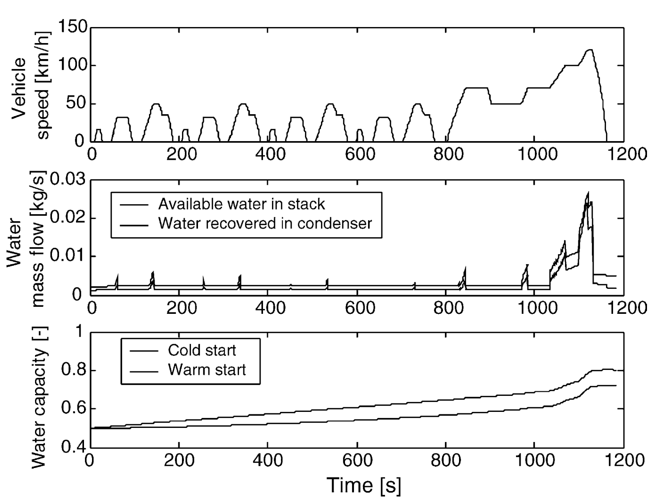

Fig. 9. Water mass flows and balance over the NEDC for a SUV. Elevation, 0 m; temperature, 20 °C.

The water balance is to some extent affected by the ambient temperature. Fig. 10 displays an example of the ambient air temperature impact on the water capacity over the NEDC. With a higher ambient temperature, 40 °C, the temperature difference between the system and the ambient is smaller than normal operation. The ability to reject heat of the condenser is therefore reduced with less water recovered for the water balance. On the opposite side of the ambient temperature scale, here 5 °C, the ability to reject heat of the condenser is larger. However, the water recovery is not as efficient as expected due to counteracting effects by other auxiliary system component thermal losses in the system. At 5 °C, less heat in the condenser can be rejected since the fuel cell stack heating requires more heat. This is why the low ambient temperature water balance is not quite as good as at 20 °C.

The relative humidity of ambient air has an impact on the water balance. In Fig. 11, the water capacity is shown for low and high ambient air relative humidities, 30 and 75%,

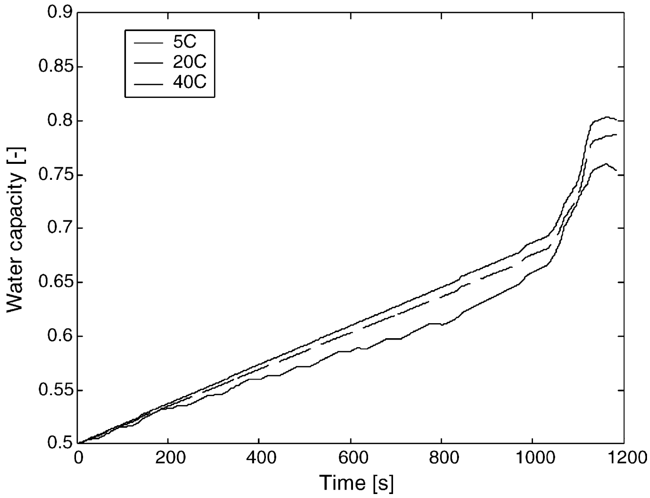

Fig. 10. The water balance (as water capacity) at different ambient temperatures over the NEDC. Elevation, 0 m; temperature, 20 °C.

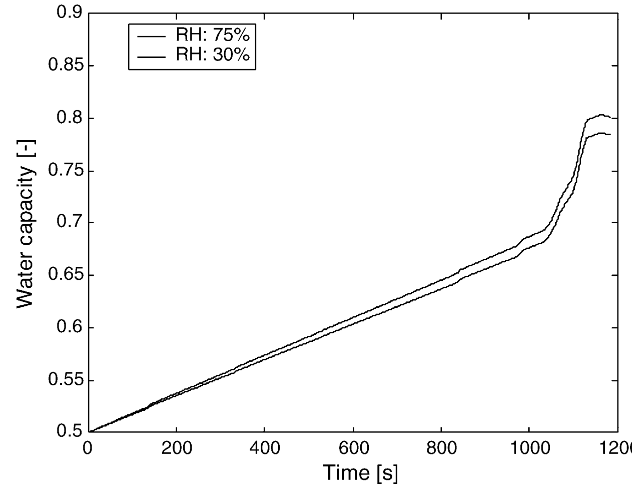

Fig. 11. The sensitivity to ambient relative humidity of the water management system. Elevation, 0 m; temperature, 20 °C.

respectively, over the US06 cycle. For the low relative humidity case, the water capacity is slightly lower than in the high relative humidity case throughout the duty cycle. At the end of the cycle, the difference between the humidity levels is only a few percent.

Ambient air temperature and cold and warm starts have only a minor impact on the vehicle fuel consumption as can be seen in Fig. 12 with about 3% difference in fuel consumption between 5 and 40 °C and about the same difference or lower between cold and warm start over the NEDC. Varying the ambient temperature at sea level did not have a significant impact on the compressor performance over the moderate-power NEDC. However, the compressor operating in the high-power US06 cycle showed sensitivity towards ambient temperature, with higher power input demand at higher ambient temperatures. This leads to the fuel consumption peaks in the US06 cycle in Fig. 12.

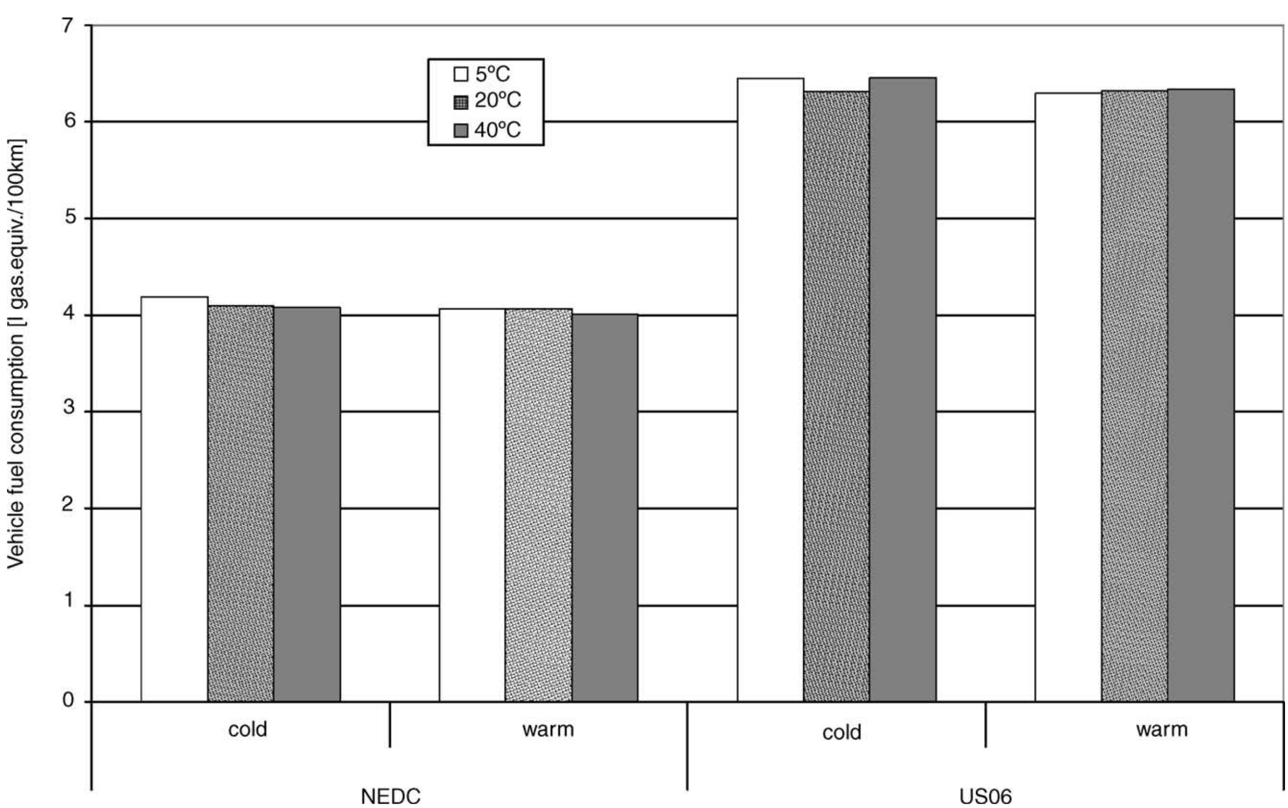

Fig. 12. Ambient temperature effects on the vehicle fuel consumption over the NEDC and US06 cycle at cold and warm starts. Elevation, 0 m.

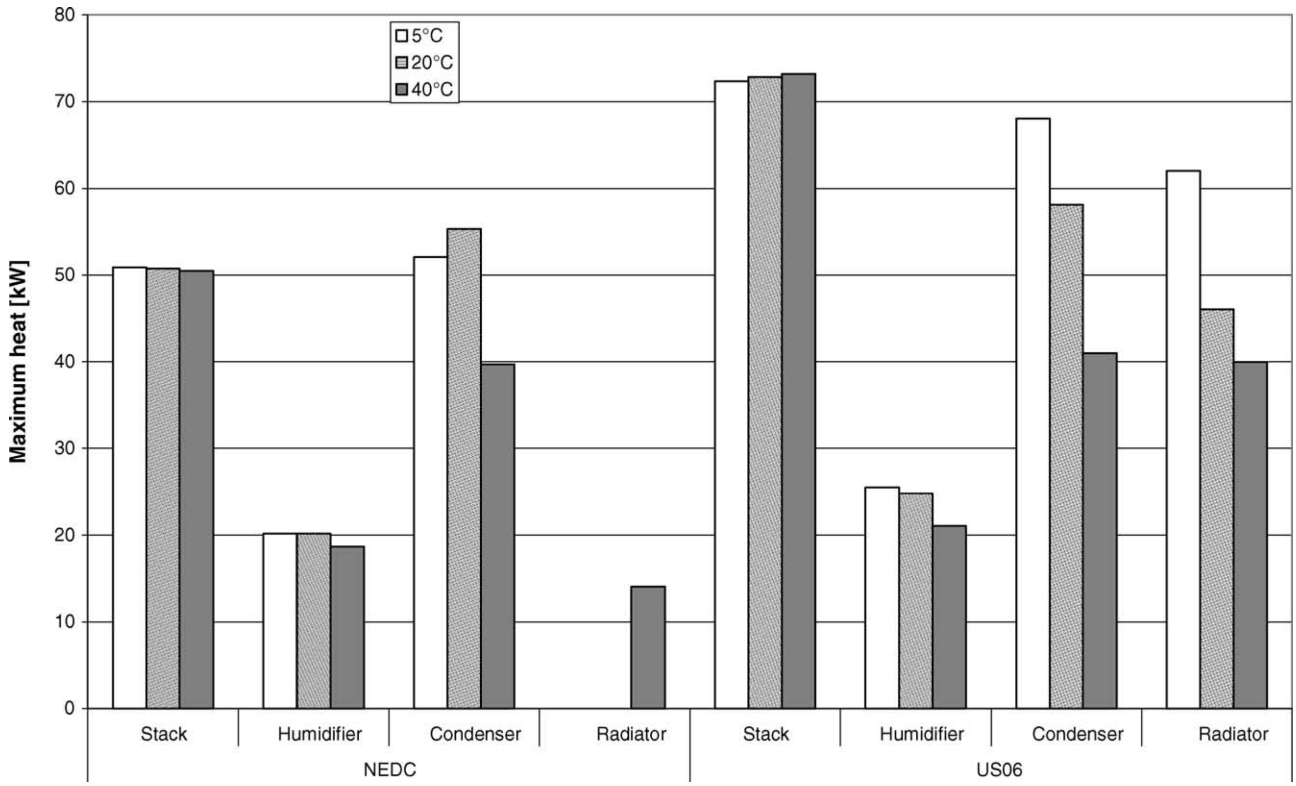

Fig. 13. The ambient temperature effect on the heat load distribution (maximum values) over the NEDC and US06 cycle. Elevation: 0 m, warm start.

The effect of ambient temperature on the heat distribution of the fuel cell system is demonstrated in Fig. 13. At cold temperatures, 5 °C, it takes longer time for the fuel cell system to heat up to operating temperature and the fuel cell will therefore not operate efficiently in the beginning of the duty cycle. Although the fuel cell stack is not affected by the change in ambient air temperature, its auxiliaries, humidifier, condenser and radiator, are. The heat for the humidifier is decreasing with increasing temperature by 7% from 5 to 40 °C over the NEDC and by 17% over the US06 cycle. In the US06 case, the heat load of the condenser and radiator drop by 35–40%. In the NEDC case, the condenser heat load increases from 5 to 20 °C due to the low-speed profile of the duty cycle but decreases markedly up to 40° C, by more than 20%, due to the lower temperature difference between the fuel cell system and the ambient. Over the NEDC, the radiator is not in use unless the ambient temperature is 40 °C. At this high ambient temperature, the heat transfer to the ambient is reduced due to lower temperature difference which leads to an increase need of rejecting heat in the radiator. In the high-speed US06 case, the condenser and the radiator heat loads decrease with increasing ambient temperature.

4. Discussion

Interactions between the heat and water management, e.g., size of various heat transfers, are important to understand in order to design an efficient fuel cell system. In addition, compressor size and airflow are important factors for the overall performance. In terms of dimensioning the system components three parameters factor in. The limiting factor for the water balance is the maximum ambient air temperature, here 40 °C, for the heat management the minimum ambient air temperature, 5 °C, and for the overall vehicle performance the maximum altitude of 3000 m.

The water capacity in this study was a function of the size of the water reservoir and the control strategy of the condenser fan. The relative humidity did not have a great impact on the water balance thanks to a good size of the water supply system.

It should be emphasized that it is not solely the ambient conditions that have an impact on the fuel cell hybrid vehicle performance. The design and control strategy also affect impact of the overall performance results. All these factors put together make the design of an efficient fuel cell system and hybrid vehicle a complex task. Here, an attempt to distinguish the different factors (ambient air temperature and pressure), relative humidity and duty cycle and to provide trends was made. Further investigation on the impact of varying ambient conditions including cold and warm starts and subzero ambient air temperatures on fuel cell vehicles need to be performed. In addition, the stoichiometric coefficient of air used in this study is rather high and impacts negatively on the compressor power demand. Reducing the air mass flow will also reduce the compressor power input.

5. Conclusions

The vehicle fuel performance is affected by parameters such as ambient conditions and duty cycle. Here, the vehicle fuel consumption, the air compressor power demand, the water management system and the heat loads of a fuel cell hybrid sport utility vehicle were studied.

The vehicle fuel consumption increases with altitude with up to 10% over the New European Drive Cycle (NEDC). On the more power demanding US06 cycle, the fuel economy drops with 19%. This reduction in fuel economy is due to the major contributing parasitic fuel cell system component, the air compressor. The operating pressure of the fuel cell system is load-following which has an impact on the performance of the air compressor at different altitudes. An increase in altitude leads to raised air mass flow and pressure ratio with an increase in compressor power demand as a result. Almost 40% of the net power output of the fuel cell system is consumed by the air compressor with this load-following strategy. This is more apparent in the high-power US06 cycle.

Ambient air temperature and relative humidity have some impact on the vehicle performance mostly seen in the heat and water management of the fuel cell system. While the heat loads of the fuel cell system components vary significantly with increasing ambient temperature, the relative humidity did not have a great impact on the water balance.

Overall, in order to maintain proper water and heat management of the fuel cell system, the components dimensions should be such as to meet the fuel cell system requirements at the minimum and maximum expected ambient temperature, in this case 5 and 40 °C, and high altitude.

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