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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

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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

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[*] 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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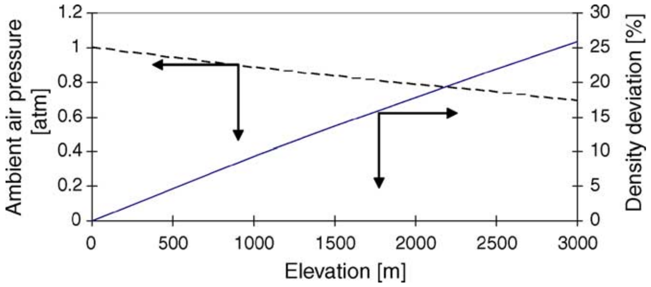

Fig. 1. The effect of altitude on ambient air pressure and density. The density is shown as deviation from the sea-level value of the density. Based on [3].

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.

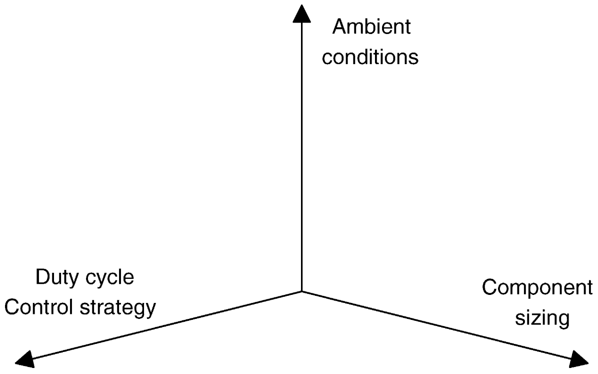

Fig. 2. Parameters impacting on fuel cell system component sizing; ambient conditions and duty cycle and control strategy.

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