Journal of Power Sources 250 (2014) 204–211

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Characterisation of a hybrid, fuel-cell-based propulsion system for small unmanned aircraft

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HIGHLIGHTS

- An experimental characterisation is presented for the hybrid AeroStack fuel-cell system.
- The electrical efficiency of the fuel cell was found to be over 50% for a large range of output power.
- The polarisation curve exhibits hysteresis effect during dynamic load changes.
- The systems' battery ensures a fast response and protects the fuel cell from starvation.
- The fuel cell recharges the battery with a peak current of 1 A.

ARTICLE INFO

Article history:
Received 28 September 2013
Received in revised form
9 November 2013
Accepted 11 November 2013
Available online 19 November 2013

Keywords:
Characterisation
Hybrid fuel-cell-based system
Unmanned aircraft systems
Polarisation curve
Dynamic response

ABSTRACT

Advanced hybrid powerplants combining a fuel cell and battery can enable significantly higher endurance for small, electrically powered unmanned aircraft systems, compared with batteries alone. However, detailed investigations of the static and dynamic performance of such systems are required to address integration challenges. This article describes a series of tests used to characterise the Horizon Energy Systems' AeroStack hybrid, fuel-cell-based powertrain. The results demonstrate that a significant difference can exist between the dynamic performance of the fuel-cell system and its static polarisation curve, confirming the need for detailed measurements. The results also confirm that the AeroStack's lithium-polymer battery plays a crucial role in its response to dynamic load changes and protects the fuel cell from membrane dehydration and fuel starvation. At low static loads, the AeroStack fuel cell recharges the battery with currents up to 1 A, which leads to further differences with the polarisation curve.

1. Introduction

Small, electrically powered unmanned aircraft systems (UAS) are currently used for a variety of reconnaissance and remote-sensing missions [1–3]. Electric propulsion is typically preferred over the use of small internal-combustion engines because of its comparatively high efficiency, low cost, and high reliability [1,2,4–6], as well as low infrared and noise levels. The energy density of commercially available batteries, however, limits the achievable endurance of battery-powered UAS; and this has motivated the development of advanced fuel-cell-based powerplant systems [2,6–8]. Several research groups around the world have designed and flight-tested fuel-cell-powered demonstrator aircraft [2,4–16]. Their research systematically reports the lack of publicly available detailed performance specifications [6–8] and demonstrates that airworthy fuel-cell-based systems require a different design strategy than automotive and stationary applications [4,17].

Aircraft typically require a large power range for different flight phases, and a fast response is required to balance the load variations [6]. However, fuel cells are generally limited in power density and can suffer from a slow dynamic response [18–24]. A hybrid system, in which a fuel cell is combined with a secondary, short-term boost capacity, such as that provided by batteries or ultracapacitors, is thus required for operationally viable systems [6,15]. These hybrid systems combine the high power density of the secondary system, ideal for short-duration peak power, with the high energy density of the fuel cell, which enables long endurance [19–21,24–28]. In a hybrid system, the advantages of each of the subsystems are exploited, which can lead to a lighter, cheaper system with improved efficiency [25–27]. Hybrid systems, however, include dynamic subsystems and passive or active power-

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http://dx.doi.org/10.1016/j.jpowsour.2013.11.017

Nomenclature

Δg_f	Gibbs free enthalpy of formation, [J mol^{-1}]
$\dot{m}_{H_2,tot}$	total H_2 mass-flow rate, [slpm]
$\dot{m}_{H_2}$	H_2 mass-flow rate (no purging), [slpm]
$\dot{n}_{H_2}$	H_2 molar-flow rate (no purging), [mol s^{-1}]
η_{el}	electrical efficiency, [−]
η_F	Faradic efficiency, [−]
η_{th}	thermodynamic efficiency, [−]
η_V	voltage efficiency, [−]
μ_f	fuel utilisation, [−]
a	number of stack cells, [−]
B	polarisation curve-fit coefficient, [V ln(A)$^{-1}$]
F	Faraday constant, [C mol^{-1}]
I	fuel-cell stack current, [A]
LHV	lower heating value of H_2, [MJ kg^{-1}]
lhv	molar lower heating value of H_2, [J mol^{-1}]
m	polarisation curve-fit coefficient, [V]
n	polarisation curve-fit coefficient, [A^{-1}]
P	fuel-cell stack power, [W]
V_0	polarisation curve-fit coefficient, [V]
R	polarisation curve-fit coefficient, [Ω]
V	fuel-cell stack voltage, [V]
A/D	analog-to-digital
d.c.	direct current
FS	full scale
LiPo	lithium-polymer
PEM	proton exchange membrane
UAS	unmanned aircraft systems

management systems, which present implementation challenges requiring proper consideration when integrating the powerplant in an (unmanned) aircraft.

Despite the documented need for detailed performance data and a hybrid architecture, most reports in the literature focus on the aircraft development and only present limited flight-test results on the performance of the propulsion system. Detailed investigations of the static and dynamic behaviour of fuel-cell power sources in UAS configurations are limited [5], and the performance of hybrid battery-fuel-cell systems for UAS is only superficially documented [6,15].

This paper describes a detailed characterisation of the Horizon Energy Systems' AeroStack[1] hybrid, fuel-cell-based powertrain, which is designed for use in small UAS [29,30]. Section 2 of the paper describes the architecture of the test bench, which has been arranged to permit future hardware-in-the-loop simulation. Section 3 presents the (static) polarisation curve of the hybrid system; and its dynamic response is described in Section 4.

2. Test-bench architecture

A schematic representation of the test bench used to characterise the hybrid system is given in Fig. 1. The hardware components tested in the current configuration are shown in the light-grey area of the figure. They consist of the AeroStack hybrid system, which comprises a fuel cell, its controller, a 6S-cell lithium-polymer (LiPo) battery, and a passive power-management board [29,30]. As illustrated in Fig. 1, the AeroStack fuel cell is supplied with high-purity (99.999%) hydrogen from pressurised bottles; and a load is applied using a direct-current (d.c.) electronic load.

2.1. Hardware components

The test bench is currently built around a hybrid AeroStack system from Horizon Energy Systems [29,30]. It includes a 35-cell proton exchange membrane (PEM) fuel-cell stack with an active area of 16.8 cm^2. The stack has a nominal power output of 200 W and can deliver up to 10 A [29,30]. Its operating voltage ranges from 32 V when no load is applied to 20 V at full load [29,30]. The fuel cell is self-humidified and operates at near-ambient cathode pressure. The anode (hydrogen side) is dead-ended so that all of the hydrogen is either consumed by the fuel-cell reaction or wasted due to leakage or purging.

The fuel-cell controller adjusts the stack temperature by controlling the speed of the cathode-supply fans, as indicated in Fig. 1. The controller also regulates periodic anode purging to maintain a high rate of hydrogen utilisation and to ensure stable, prolonged stack performance [30]. Anode purging is required to remove inert gases, liquid water and contaminants, as well as any excess hydrogen from the fuel-cell anode and to maintain internal pressure at appropriate levels [5,21,31–35]. Finally, the controller short-circuits the fuel cell every 10 s. This increases the stack efficiency and forms part of the self-humidification process of the fuel cell [36]. Short-circuiting is executed through a solid-state switch on the controller that is connected across the fuel cell's output terminals [36]. During short-circuiting, the load is disconnected from the fuel cell for about 50 ms, and the fuel cell does not supply power to either the load or its own controller [36]. The LiPo battery is included in the circuit to provide continuous power to the load and controller and to prevent total loss of power to either. The fuel-cell controller has a capacitor to smooth the power output, but its capacity is not sufficient to bridge the 50-ms gap completely [36].

Besides bridging the short-circuiting period, the 6S-cell ThunderPower 1350-mAh (25C) LiPo battery pack can deliver an additional 400 W for 2 min to meet the high-power requirements during UAS take-off or climbing [30]. The battery augments the power output from the fuel cell through the power-management board, and the total output power is limited to 800 W for approximately 1 min to prevent its Schottky diode from overheating [30]. The board additionally controls the recharging of the battery when excess power is available from the fuel cell.

2.2. Interface components

In the experimental arrangement described here, the interface components provide the physical and communication link between the software and the previously described hardware components. The electrical connection between the hybrid AeroStack system and the control software is made by use of a BK Precision 8514 d.c. electronic load [37]. This programmable multi-mode load can draw up to 1200 W and is rated up to 120 V and 240 A. In constant-power mode, the load has an accuracy of 1.0% ± 0.1% of the full scale (FS) [37].

As the AeroStack system does not provide a measurement of the hydrogen flow rate, a mass-flow meter is included on the test bench, so that the efficiency of the fuel cell can be determined. An Apex AX-M4SLPM-D5 flow meter has been selected because it offers a high repeatability (0.2% FS), coupled with a very high

[1] Horizon Energy Systems has recently rebranded its products, adopting the name AeroStack for the fuel-cell hybrid system and using AeroPak for the system including a chemical-hydride tank. To reflect this, the name AeroStack is used here.