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Direct methanol fuel cell (DMFC) and H_2 proton exchange membrane fuel (PEMFC/H_2) cell performance under atmospheric flight conditions of Unmanned Aerial Vehicles

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A B S T R A C T

Recently, there has been growing interest in fuel cell implementation on aircraft, particularly for Unmanned Aerial Vehicle (UAV) propulsion. The performance of both fuel cell types, cathode air-breathing H_2 Proton Exchange Membrane Fuel Cells (PEMFC/H_2) and passive Direct Methanol Fuel Cells (DMFCs), is dependent on atmospheric conditions such as pressure, relative humidity and temperature. In this study, models at the single-cell level have been used to simulate the corresponding polarization curves on flight conditions, which constitutes a contribution to the use of fuel cells in UAV. After validating these models, several cases of interest relating to UAV operation have been considered, such as cruise flight at different altitudes and horizontal flight when crossing clouds, to compare the performance of both types of fuel cells. Fuel cell temperature has been controlled to avoid high performance degradation. The results show that the effects of atmospheric flight conditions are more important for PEMFC/H_2 than for DMFCs. Low pressure affects PEMFC/H_2 performance to a greater extent than DMFC performance. Atmospheric relative humidity affects PEMFC/H_2 performance, especially at high cell temperatures, whereas DMFC performance is barely affected. Although performance is lost, it is possible to operate fuel cells in UAV propulsion systems at low-medium altitudes.

1. Introduction

In recent decades, increased interest in finding power systems that use fuels other than oil derivatives has prompted the study of fuel cells, with the aircraft industry generally showing the greatest interest. Although air traffic is only responsible for 3% of total greenhouse emissions, aircraft manufacturers are working to achieve more efficient aircraft, leading to more electric or all-electric aircraft concepts. Unmanned Aerial Vehicles, also known as Remotely Piloted Aircraft Systems (RPAS), are of particular interest for the incorporation of fuel cells into aircraft propulsion systems. This is especially true for small UAVs with low manoeuvrability and long operation times. These are currently the most widely developed systems, of interest in both military and civilian/commercial applications. Airships, and stratospheric airships in particular, are another potential field of application for fuel cells [1].

Besides causing low environmental impact, the use of fuel cells in unmanned aircraft offers clear benefits that are intrinsic to these types of devices, such as their modularity, low noise levels and increased endurance or flight time, which is one of the main problems with UAVs [2].

There have been some actual UAV flights propelled by fuel-cell-based systems. Bradley [3] (PEMFC/H_2) and Kang's [4] (DMFC) developments are examples in which atmospheric conditions were not relevant due to the low altitudes reached. Hordé [5] undertook an experimental and numerical study of sensitivity to altitude in PEMFC/H_2 focused on aviation. Fuel cell performance was analysed at different altitudes while varying pressure and stoichiometry and employing a compressor. This study concluded that the degradation of the polarization curve was caused by low pressure associated with high altitudes. Bégot [6] performed climatic tests focusing on aircraft flight conditions and temperature variations,

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Abbreviations

AFGL	Air Force Geophysics Laboratory
DMFC	Direct Methanol Fuel Cell
GDL	Gas Diffusion Layer
HALE	High Altitude Long Endurance
ICAO	International Civil Aviation Organization
ISA	International Standard Atmosphere
MALE	Medium Altitude Long Endurance
MEA	Membrane Electrode Assembly
MR	Medium Range
PEMFC/H_2	H_2 Proton Exchange Membrane Fuel Cell
ppmv	Parts Per Million Volume
RH	Relative Humidity
RPAS	Remotely Piloted Aircraft Systems
SR	Short Range
UAV	Unmanned Aerial Vehicle

describing malfunctions due to ice formation at very low temperatures. Novillo [7] reviewed some concepts relating to fuel cell integration in aircraft, highlighting the importance of water management for membrane humidification in connection with fuel cell performance and remarking that the elimination of external humidification leads to a significant reduction in system complexity, and therefore weight. Fang [8] developed an equivalent circuit model for a DMFC, varying the methanol concentration and operating temperature, and analysing the model's application to a DMFC implemented on a microaircraft such as a UAV.

Other research is not aimed at aviation, but is significant due to the study of the influence of different atmospheric variables on fuel cell performance. Rinaldi [9] performed several tests on a PEMFC/H_2 in a climatic chamber under different temperature and relative humidity (*RH*) conditions. Barelli [10] proposed a novel semi-empirical model in order to analyse PEMFC/H_2 performance with certain ranges of pressure, temperature, *RH* and CO content of H_2. The suitability of high *RH* when operating at high cell temperatures was highlighted in order to avoid low performance. Yuan [11] developed a 3D PEMFC/H_2 model to study the effects of operating parameters (pressure, temperature, relative humidity and air stoichiometric ratio). The influence of water management was highlighted, as well as the risk of flooding in the event of excess humidification. Tohidi [12] reached similar conclusions after employing a 1D PEMFC/H_2 model. Iranzo [13] performed several tests on a commercial fuel cell under different operating conditions: *RH* (anode and cathode), cathode stoichiometry and cell current density. The effects were assessed with neutron imaging. It was found that cathode *RH* had a much greater effect on cell water content and overall performance than anode *RH*. Ko [14] investigated the effect of operating pressure and relative humidity (at a constant temperature) on water distribution, and its effect on the performance of PEMFC/H_2. Salva [15] validated a 1D model with experiments that involved varying operating conditions such as cathode stoichiometry, anode and cathode *RH* and pressure. Yousefi [16] studied the influence of passive DMFC cell orientation on the flooding phenomenon, and therefore on performance. Some environmental conditions, such as *RH* and temperature, were also evaluated during the tests. The need for further research on the effects of environmental pressure on passive DMFC performance was one of the conclusions.

The novelty of this study lies in the fact that even though different researchers have investigated the influence of atmospheric parameters on PEMFC/H_2 and DMFCs, there are no reports of studies focusing on UAV flight conditions (i.e., pressures lower than unit for both types of fuel cells, or *RH* related to altitude), or a comparison of both types of single cells in terms of performance degradation as a function of altitude. This is the objective and the relevance of this study, through the development of 1D models to investigate the effects of pressure, temperature and *RH* so that they are linked to UAV flight altitude. This will be useful for the development and operation of UAVs with propulsion systems based on these types of fuel cells.

After reviewing the state of the art and analysing the feasibility of implementing different types of fuel cells on UAVs [17], an altitude sensitivity study of two types of fuel cells, PEMFC/H_2 and DMFCs, was developed, comparing both types under the same atmospheric conditions. They are considered cathode air-breathing cells in this study, with the aim of avoiding the extra weight of carrying pressurized oxygen tanks on board the UAV. For the same reason, air compressors are not taken into account. At very high altitudes (i.e., 10000 m), the use of tanks is mandatory [18]. Low-temperature PEMFC/H_2 feature a quick start, provide high current, high specific energy density and low specific power density. The fuel used is hydrogen stored in different ways.

On the other hand, DMFCs provide lower power density and efficiency than PEMFC/H_2, but offer greater simplicity in addition to higher energy density. In this study, the DMFC is passive due to certain advantages for the UAV, especially in terms of weight, absence of moving parts, compactness, and decreased energy losses due to the reduction of ancillary devices (lack of methanol pump) [16]. Thus, its lower performance is partially compensated by those advantages.

According to Table 2 in Ref. [17], the power density of PEMFC/H_2 stacks embarked on UAV propulsion systems are in the (50–2000 W/kg) range. The only example of a DMFC UAV application found in the literature [4] (UAV 15.96 kg, DMFC 200 W) has a nominal power density of 72.02 W/kg (53.60 W/kg, including the weight of auxiliary systems). A comparable PEMFC/H_2 system is described by Yang [19] (UAV 21.19 kg, PEMFC/H_2 750 W), and has a nominal power density of 381.30 W/kg (112.14 W/kg, including the weight of auxiliary systems). In these examples, both types of cells are supported by batteries. The decrease in power density due to the auxiliary systems becomes less important for the DMFC case, due to the simplicity of its auxiliary systems.

The vast majority of fuel cells are designed to operate on the ground, so it is of vital interest to study how the variation of atmospheric conditions during UAV flight affects fuel cell performance. For this purpose, this study defines polarization curve models for both types of fuel cells. This will allow for later use when studying 'stacks'. Thus, analysing the results obtained by varying parameters such as pressure, relative humidity and operating temperature makes it possible to reach conclusions about the influence of those parameters on fuel cell performance for different UAV flight cases. Atmosphere models are therefore necessary in order to establish variations of those atmospheric magnitudes.

2. Atmosphere models

The first atmosphere model used in the simulation is the International Standard Atmosphere (ISA) [20]; see Fig. 1.

The ISA model divides the atmosphere into layers with linear temperature distributions. This model includes atmospheric temperature T and pressure p, but not *RH*. Temperature and pressure are given by expressions in two stages: 0–11000 m and 11000–25000 m. This model is used in aviation; in fact, the International Civil Aviation Organization (ICAO) published the 'ICAO Standard Atmosphere' [21] with the same model as the ISA, but extended to 80000 m.