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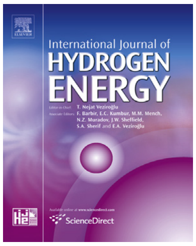

Use of fuel cell stacks to achieve high altitudes in light unmanned aerial vehicles

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ABSTRACT

A study is presented to determine if substituting an internal combustion engine (ICE) by an electric motor powered by a fuel cell stack can be a viable option to increase the service ceiling of an available light unmanned aerial vehicle (UAV), extending it to 10,000 m. As a first condition, the stack has to be capable of supplying the minimum power required for horizontal leveled flight at this altitude, which is a function of the UAV total mass. A second step examines if the UAV can transport the energy required to reach the desired service ceiling without exceeding the maximum mass that can be loaded, considering that both hydrogen and oxygen have to be carried on-board. A particularly light PEM fuel cell stack is proposed as a suitable power source. A realistic system is described to store the required amount of reactant gases maintaining the mass below the allowable limits. Results indicate that with its aerodynamic characteristics, the UAV should be capable of ascending up to 10,000 m with the described fuel cell and gas storage system. Some multivariable maps that include service ceiling, total payload and required power are provided to perform this type of analysis.

Introduction

Development of aerial vehicles powered by fuel cells responds to the request of finding new ways to supply energy with high efficiency and low pollutant emissions. The possibility of using fuel cell stacks in power units of crewed aircrafts is still a future objective, but manufacturing unmanned aerial vehicles (UAVs) with these power sources can be achieved with current technology. Depending on flight ceiling and duration, size and weight, UAVs can be divided in micro, tactic, strategic and UAVs for special tasks [1]. Potential applications of these devices are multiple, both in civil or military missions. The fact that they can be light, without human pilots and that most of their controls are electrically driven, makes them an ideal test bed for powerplants based on fuel cells. In the last years, some papers have reported successful flight tests of light UAVs with electricity supplied by fuel cells [2–4]. However, the number of tests is still small and most of them were restricted to short duration flights at low altitude.

High altitude flights of small UAVs pose some specific challenges related to the particular atmospheric conditions. Atmospheric pressure at a cruising altitude of 10 km is only

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Nomenclature

Latin alphabet

a	temperature gradient in the troposphere, K m^{-1}
AR	wing aspect ratio
b	wingspan, m
C_L	lift coefficient
C_{Lmax}	maximum lift coefficient
C_D	drag coefficient
C_{D0}	parasitic drag coefficient
D	drag force, N
e	Oswald efficiency
g	gravity acceleration, m s^{-2}
h	height above the sea level, m
k	ratio of indicated power
L	lift force, N
n	weight factor
M_F	aircraft frame mass, kg
M_{H_2}	mass of hydrogen storage system, kg
M_{O_2}	mass of oxygen storage system, kg
M_{Total}	total mass of the storage system, kg
p_h	pressure at the given height, Pa
p_{SL}	pressure at sea level, Pa
P	aircraft power, W
P_{Prop}	propeller power, W
P_{SL}	aircraft power at sea level, W
P_{FC}	fuel cell power, W
R	air gas constant, m^2 s^{-2} K^{-1}
RC	rate of climb, m s^{-1}
S	wing surface, m^2
T_h	temperature at the given height, K
T_{SL}	temperature at sea level, K
T	thrust force, N
v	aircraft velocity, m s^{-1}
v_{stall}	stall (minimum) velocity, m s^{-1}
V_{H_2}	volume of stored hydrogen, l
V_{O_2}	volume of stored oxygen, l
W	aircraft weight, kg

Greek letters

α	attack angle
β	flight angle when T and v are aligned
δ	power adjustment value
γ	trajectory angle
$\eta_{DC/DC}$	efficiency of the DC/DC converter
η_m	engine mechanical efficiency
η_{motor}	efficiency of the electric motor
η_{trans}	efficiency of the transmission
η_{Prop}	efficiency of the propeller
θ	pitch or elevation angle
κ	angle between τ_e and the longitudinal axis
ρ	density, kg m^{-3}
ρ_{SL}	density at sea level, kg m^{-3}
τ_e	thrust force, N

0.26 bar, and oxygen partial pressure is 0.05 bar. This imposes severe limitations to the operation of atmospheric reciprocating internal combustion engines (ICE). Low pressures decrease air density, diminishing the intake air charge to the engine. A low intake charge reduces, in turn, the engine volumetric efficiency, and less power is delivered [5–7]. The constant loss of power as a function of altitude becomes much more critical in small ICEs than in large ones, where the decreasing pressure effect can be balanced with an air compressor. Unfortunately, small UAVs usually powered by ICEs with small cylinder capacity cannot incorporate compressors or other alternative systems to increase the intake pressure. Such systems require a significant fraction of the generated power, and contribute to increase the total aircraft payload, which cannot be afforded in small UAVs. The combination of electric motors with fuel cells can be an advantageous alternative to mini-ICEs. Efficiency of electric motors is far better than that of an ICE, for any rpm range. Besides, fuel cells can be designed to operate at high altitudes, taking into account the special requirements for this application. As in all types of aircraft and flight conditions, weight is an essential issue. Fuel cells are required to be as light as possible, but the need to carry on-board bottles to store the reactant gases or alternative systems to generate them *in situ* has also to be taken into account. If the UAV has to reach high altitudes, not only hydrogen but also oxygen has to be transported. This is so because oxygen concentration in the stratosphere is too low to adopt open cathode configurations. Besides, atmospheric temperature has also to be considered in the design of the cooling system.

The objective of this research is to provide adequate tools to determine if for some specific aerodynamic characteristics, a light UAV will be capable of reaching an altitude of 10,000 m powered by a fuel cell and carrying onboard the required amount of reactant gases.

Determination of the minimum required power

In daily operation, an aircraft engine can provide a certain maximum power for a determinate time (depending on fuel reserves). According to it, the pilot has to program the flight, adjusting velocity, height, or climbing and descending strategies so that neither maximum power nor flying time are exceeded. In the present case, a fuel cell stack is to be adapted to a specific UAV, so, first, the minimum required power has to be determined. To calculate it, basic aerodynamic equations will be used, in the understanding that this work does not pretend to study in depth the theory of aircraft. Initially, a real UAV with the characteristics described in Table 1 will be considered.

The subsequent analysis will determine if this aircraft is capable of reaching high altitudes with a fuel cell stack of a specific power.

A UAV can fly with six degrees of freedom that have to be controlled: displacement along the three axes and rotations around them. Primary control elements are ailerons in the front wings, elevators on the horizontal tail and rudder in the vertical tail. To simplify the calculations, it will be assumed that the UAV only moves along its longitudinal and normal

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