Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Design methodology for a PEM fuel cell power system in a more electrical aircraft

D. Guida [a,*], M. Minutillo [b]

[a] Centro Italiano Ricerche Aerospaziali, Via Maiorisi, Capua, Italy
[b] University of Naples Parthenope, Centro Direzionale Isola C4, Napoli, Italy

HIGHLIGHTS

- The sizing procedure for a PEM FC power system for aviation applications is presented.
- The power system is installed in a containment chamber with fixed climatic conditions.
- The specific energy of the FC power system is higher than that of a battery system.
- The calculated specific energy results to be equal to 0.51 kW h/kg.

ARTICLE INFO

Article history:
Received 20 April 2016
Received in revised form 30 September 2016
Accepted 24 October 2016
Available online xxxx

Keywords:
PEM fuel cell
Electric aircraft
Specific energy
Optimization procedure

ABSTRACT

In recent years the concept of "more electric aircrafts" has established itself increasingly and the electrical power systems for aircrafts are in progress. In this context, fuel cells represent a valid source of electric power for the advantages in terms of pollution emissions, noise reduction and fuel consumptions.

In this study, the authors analyzed the feasibility, from the specific energy point of view, in using a PEM fuel cell power system as APU unit in a more electrical aircraft with respect to a battery system installation. The proposed fuel cell system has a modular architecture and consists of fuel cell stacks, air compressors, heat exchangers, compressed hydrogen tanks and auxiliary batteries.

The analysis has been performed by applying a design methodology based on an optimization procedure concerning the size and the efficiency of each power system component in order to reach the maximum specific energy (higher than 500 W h/kg).

Moreover, a "black-box"-type model of the power system has been developed to support the optimization methodology in the evaluation of its performance in terms of electric power production, heat production, auxiliary systems consumption and hydrogen consumption.

Results pointed out the advantages of the PEM fuel cell application in a more electric aircraft; as a matter of fact for assigned mission requirements, according to the specifications defined in the Long Endurance Demonstrator (LED) project promoted by CIRA (Italian Aerospace Research Centre), the specific energy of the designed power system results to be equal to 0.51 kW h/kg. This value is very interesting if compared to the specific energy of commercial LiPo batteries characterized by 0.2 kW h/kg.

1. Background and scope

The continuing growth in air traffic has made environmental pollution one of the most critical aspects of commercial aviation today. It is generally accepted that significant improvements to the environmental sustainability of aircraft will be needed if the long-term growth of air transport has to be sustained.

Nowadays, the increasing public awareness sensibility in environmental issues has been implementing in the main European funded research programs. As a matter of fact, in the Flightpath 2050, a report in which the European Vision for Aviation [1] is outlined, one of the five challenges, that Europe must face, is "Protecting the environment and the energy supply". In order to win this challenge, two of five goals require that:

* Corresponding author.
E-mail address: d.guida@cira.it (D. Guida).

http://dx.doi.org/10.1016/j.apenergy.2016.10.090
0306-2619/

Please cite this article in press as: Guida D, Minutillo M. Design methodology for a PEM fuel cell power system in a more electrical aircraft. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.10.090

Nomenclature

Symbols and Acronyms

M	Mac number
APU	auxiliary power unit
PEM	polymer electrolyte membrane
FC	fuel cell
LED	long endurance demonstrator
CIRA	Italian Aerospace Research Centre
LiPo	lithium polymer battery
W_{ob}	electric load
t_{miss}	mission duration
N_{stack}	fuel cell stacks number
M_{stack}	total fuel cell stacks mass
$Mass_{unit_{Stack}}$	single fuel cell stack mass
M_{H_2}	hydrogen molecular mass
Num_{Tank}	hydrogen tanks number
$Tank_{max_{H_2}}$	hydrogen mass storable in one tank
M_{Tank}	total Tanks mass
$\dot{m}$	air flow rate
$\dot{n}_{H_2}$	hydrogen molar flow rate
ς	multiple H_2/O_2 stoichiometric ratio
M_{AIR}	air molecular mass
$AirFlow_{unit_{comp}}$	air flow rate processable by one compressor
Num_{comp}	compressors number
M_{comp}	total compressors mass
$Mass_{unit_{batt}}$	single battery mass
$W_{unit_{batt}}$	single battery power
CellA1000	cells number in one fuel cell stack
HE	heat exchanger
$M_{mass\_unit\_POW\_HE}$	thermal-power/weight ratio
α	power percentage reachable by the auxiliary system
η	efficiency
ρ	air density
ρ_e	system specific energy

1. “In 2050 technologies and procedures available allow a 75% reduction in CO_2 emissions per passenger kilometer and a 90% reduction in NOx emissions. The perceived noise emission of flying aircraft is reduced by 65%. These are relative to the capabilities of typical new aircraft in 2000.”
2. “Aircraft movements are emission-free when taxiing.”

Moreover, in the European Aviaton Enviromental Report 2016 [2], two more specific issues are introduced. These regard the “Technology and Design” (it means “Reductions in aircraft noise and emissions via EU research programs, Clean Sky, and environmental technical standards”) and “Sustainable Alternative Fuels”.

The latter topic aims at developing new sustainable fuels as a means to: (a) improve air quality; (b) mitigate climate change; (c) diversify energy supply.

In order to satisfy these requirements it is needed to conceive aircraft “more green” by means of the electric energy. Thus, it is possible with:

- a “more electrical aircraft” in which a rate of the energy needed by the aircraft is electrical;
- an “all electrical aircraft” that is an aircraft in which all the requested energy is electrical.

This new scenario will have a great impact on propulsion systems design criteria. In fact, when there were no strong environmental constrains, since the relevance of weight in aeronautical design, propulsion systems designs were based on endothermic engine fuelled by fossil fuels because of their high specific power and energy.

In the future, new concepts both for electrical motor and for energy storage systems must be found in order to achieve specific power and energy comparable with one of present systems.

About the electric motor, recently Siemens has announced a new electric motor with a very high value of specific power (5 kW/kg) even greater than a typical endothermic diesel engine for general aviation (about 1 kW/kg).

New projects, mainly in the framework of Clean Sky 2 program, aim at developing new electric motors with specific power up to 10 kW/kg [3].

The system that mainly needs further improvements is undoubtedly the energy storage system. In fact, nowadays this one is based on batteries that are characterized by a very low energy density (about 200 W h/kg); this is the reason for which aircraft propulsion systems are still based on endothermic engine.

Nevertheless, some researchers, such as Stoll et al. [4], are interested in the electrical propulsion as an attractive solution to explore new concepts in aeronautical design. In details, electric engine are “Scale-free efficiency and power to weight”. Thanks to this circumstance, the propulsion can be “distributed” along the leading edge of the wing increasing a lot the lift coefficient and so improving some aircraft performances. Moore in his study [5] considered to use a battery system with a specific energy is of 400 W h/kg as electric energy storage system. This value could be reached at 2025, considering that batteries increase their specific energy up to 8% per year.

In this study, the authors aim to demonstrate the feasibility, from the specific energy point of view, in using a PEM fuel cell power system as APU unit in a more electrical aircraft with respect to a battery system installation. The fuel cell system has a modular architecture and consists of fuel cell stacks, air compressors, heat exchangers, compressed hydrogen tanks and auxiliary batteries.

This analysis has been performed by applying a design methodology based on an optimization procedure concerning the size and the efficiency of each power system component in order to reach the maximum specific energy (higher than 500 W h/kg).

1.1. A more electrical aircraft

The idea of a more electric aircraft implies the increasing use of electric power to drive aircraft subsystems that, in the conventional aircraft, are driven by a combination of mechanical, hydraulic and pneumatic systems. Thus, the aim in promoting a more electric aircraft is to increasingly replace the non-electrical power in the aircraft with electricity [6–8].

Currently, electrical power is generated through the use of auxiliary power units (APUs) or by a generator connected to the high-speed turbine shaft of an aircraft engine. However, there are disadvantages to each of these methods. APUs are not very efficient and are large sources of heat and carbon emissions. The use of a generator connected to the aircraft engine reduces the power available for the flight and can justify the use of an engine larger than the one would otherwise be required.

In order to avoid these problems, fuel cell systems could replace engine driven generators to supply electric power on board.

Please cite this article in press as: Guida D, Minutillo M. Design methodology for a PEM fuel cell power system in a more electrical aircraft. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.10.090