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Multifunctional fuel cell system in an aircraft environment: An investigation focusing on fuel tank inerting and water generation

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ABSTRACT

Implementing a proton exchange membrane fuel cell (PEMFC) into an aircraft environment is a challenging task. In order for aircraft manufacturers and airlines to realize the ecological and economic benefits of this technology, it is necessary to make use of the multiple functions that a fuel cell system can provide. In addition to the main product of electrical energy, the fuel cell is capable of delivering further products, which are useful in an aircraft environment. The waste products – water vapor, heat and oxygen-depleted air (ODA) – at the cathode exhaust are valuable for use on board a commercial airplane. This paper describes the multifunctional approach, points out the advantages of the operation strategy as well as describes a prototype system for the multifunctional use of a PEM fuel cell on board a commercial airplane. The stable operation of the aforementioned system was successfully demonstrated in various tests. The emphasis of the work in question is on water and ODA generation/conditioning.

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1. Introduction

The implementation of a low temperature proton exchange membrane fuel cell (PEMFC) on board a commercial aircraft is a promising approach to decreasing emissions and to a more efficient aircraft. For the foreseeable future, fuel cell (FC) systems do not have the power density needed to replace the main engines, but could replace on-board power generators like the auxiliary power unit (APU). Following a general trend, aircraft manufacturers are trying to replace hydraulic systems with electrically driven systems. Modern aircraft, which are increasingly electrically operated, require more electrical power. Fuel cells can provide the additional electric power needed with superior electrical efficiency.

In order to implement this application within the challenging environment of an aircraft, it is necessary to improve the overall performance and use the multiple functions of the FC in order to justify the additional fuel (H_2) and weight compared to the conventional production of electric power on board. In addition to electrical energy, the fuel cell provides additional interesting products which are useful in an aircraft environment such as water and oxygen-depleted air (ODA). This paper will present a multifunctional prototype FC system for ODA and water generation. A new multifunctional system architecture was planned, installed and tested in the test facilities of Airbus/German Aerospace Center (DLR) in Hamburg, Germany. The goal of the investigation was to showcase the operation of an FC as a device with multiple functions, which provides a demonstration of the overall usefulness of the FC in an aircraft environment. The main focus of the investigation was water and ODA generation/conditioning.

2. State of the art

Electrical consumption on board of an aircraft is supplied by the APU during ground operation or by the main engines during flight. The electrical efficiency of generation from the main engines is 30–40% in the best case [13]. Ground operation of the APU is in most cases below 20% [13]. Furthermore, noise and exhaust emissions (mainly CO_2 and NO_X) are emitted [10,13].

The current safety approach to prevent combustion within jet fuel tanks is to eliminate as many ignition sources as possible. Since many electrical devices like fuel pumps, level sensors or valves are mandatory to ensure the aircrafts operation, it is not possible to eliminate all risks [3]. Additional external environmental effects, such as lightning, cannot be prevented. If the vapor space created above the fuel is flammable, the level of safety is limited, as Fig. 1 shows.

Currently, the water supply on board commercial airplanes is ensured through the use of water tanks which need to be filled prior to take off and which increase the jetliners take-off weight.

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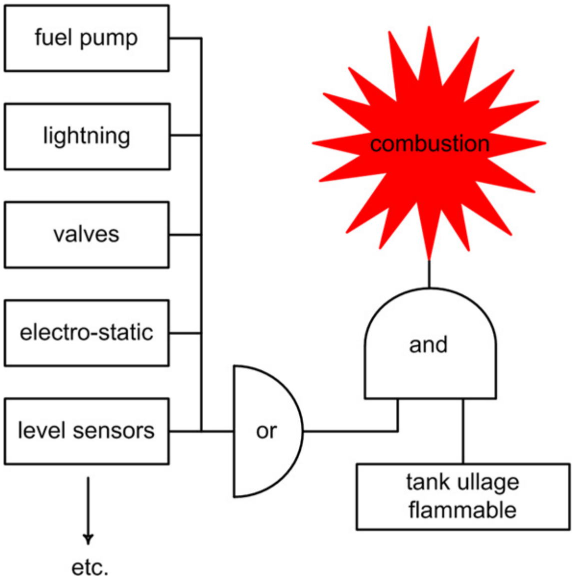

Fig. 1. Hazards of fuel air mixture combustion.

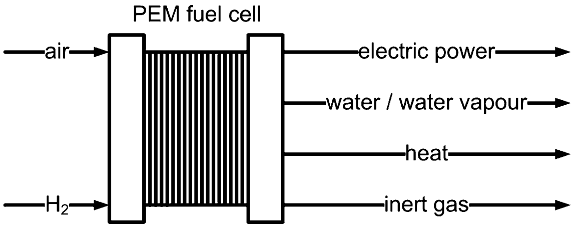

Fig. 2. Educts and products of PEM fuel cell systems.

Airlines are dependent on the water quality the airports supply and do not have the ability to control water quality themselves. In some cases water quality provided by the airports is unsatisfactory and may be contaminated with bacteria, which can endanger passenger health [15]. In order to protect customer health, airlines carry enough water to last for the return flight to the home airport without loading water at the destination. In some cases this can be over 1700 L for a long range Boeing aircraft [15].

3. The multifunctional concept

Electric power is not the only item, which is produced while operating a PEMFC. There are three additional products which are generated and can be used in an aircraft environment (see Fig. 2).

The electrical power generation by a PEM FC system including all peripheral loads can reach electrical efficiencies of up to 50% [14], which is certainly more efficient than the production with an APU or the main engines. Furthermore, the FC only emits ODA and water vapor but no CO_2, NO_X or other environmentally harmful gases [8]. By replacing on-board power generators like the APU with a fuel cell, noise emissions during ground operation are minimized, in addition there are advantages such as improved electrical efficiency and lowered emissions.

The emitted water and water vapor can, if condensed, be used in lavatories, galleys and for humidification. Since the produced water is demineralized, it is especially adequate for humidification purposes. If high quality materials are used which conform to the requirements of the Food and Drug Association (FDA), the water that is produced is relatively clean. Only a minimum level of pretreatment, such as pH adjustment, is needed to meet Environmental Protection Agency (EPA) standards for drinking water [4].

Table 1
Overview of electrical consumers on board a Boeing 787.

Pressurization	250 kW
Galley forward	40 kW
Galley aft	60 kW
Entertainment system	20 kW
Sum	390 kW

The new Boeing 787 (B787) is an example of a More Electrical Aircraft (MEA) where more and more functions on board are electrically supported. As opposed to all other Boeing models the air pressure at high altitudes inside the B787 cabin is not supplied by bleed air from the engines. Instead a compressor pressurizes ram air to provide the fresh air demand for passengers [11]. More than 25% of the 1 MW the engine generators can supply are used during flight for cabin pressurization [11] which equals 250 kW. Table 1 shows four more major electric consumption points on board a B787.

Using a flight from John F. Kennedy Airport (JFK) to San Francisco Airport (SFO) which takes about 5 h for a distance of 4139 km [11] as an example, the needed electrical energy to supply the consumption points shown in Table 1 can be calculated as follows.

$$Q_{\text{dot}} = 390\ \text{kW} * 5\ \text{h} = 1950\ \text{kWh}$$

A PEM fuel cell delivers about 0.5 L of water per kWh of generated electrical power, depending on the condensation temperature [14]. Therefore it is theoretically possible to produce 975 L of drinking water on a flight from JFK to SFO. A B787 can carry up to 1022 L of fresh water [11]. It has been demonstrated that the amount of water produced by the PEM is sufficient considering that the range of a B787 is 15,200 km [1] where even more water could be produced than the B787 water tanks are able to carry. It would not be necessary to fill the water tank prior to take off, if the FC water is used. Using this method, the starting weight of a commercial aircraft could be reduced significantly.

Furthermore, the airlines could control the water quality they provide on board, eliminating their dependency on the quality of the water supplied by the airport operator as described in Section 2.

New regulations set by the Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) force aircraft manufacturers as well as aircraft operators to introduce further measures to reduce flammability within the fuel tanks, such as inerting the vapor space inside the fuel tanks [5,6]. In order to meet the FAA and EASA standards it is necessary to prevent the development of flammable gas mixtures within the tank during operation of the main engines. Therefore the ODA provided by the fuel cell could be used as inert gas to fill the ullage which is created while drawing fuel from the tank during aircraft operation. This eliminates the problem of critical fuel air mixtures within the tank. The balanced approach (see Fig. 1) of inerting the ullage results in a higher level of safety by avoiding possible ignition due to lack of oxygen [3].

The emitted heat from the electrochemical process within the FC can be used for wing anti-icing or warm water production [2,14].

3.1. Inert gas generation

By reducing the fuel cells air stoichiometry (λ) it is possible to attain oxygen concentrations of 10 vol% at the cathode exhaust [14]. The produced ODA can be injected into the fuel tanks filling the vapor space. The low oxygen content created within the ullage

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