FUEL CELLS ON ALTERNATIVE NON-OIL FUELS FOR GAS TURBINE ENGINES OF AN ADVANCED CIVIL AIRCRAFTS

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Abstract

There are presented the results of research the optimal design of auxiliary power unit (APU) for perspective "electrical aircraft". The various APU are based on the solid oxide fuel cells (SOFC) and gas turbine on alternative non-oil fuel and kerosene. The analytical hierarchy process is used for comparing the APU design and for selecting the optimal APU. The weight impact of APU design on aircraft as a sum of mass of APU and fuel and is the main criterion for APUs comparison. It is shown that the APU on solid oxide fuel microcells fueled by products of ethanol steam conversion have a minimal weight impact on middle range aircraft. In opposite of gas turbine APU all APUs on SOFC can supply all on-board consumers in electric power at all range of flight altitudes.

1 Introduction

The idea of "more electrical" aircraft leads to necessity of usage of the auxiliary power units (APU) based on fuel cells (FC). Now there are offered a many different the APUs based on different types of FC [1-9] which should be compared with the APU on gas turbine and on combined steam and gas turbines [10].

The problem of choosing optimal APU design can be solved by comparison of the advantage and imperfection of the different power units. It should be noted that the gas turbine APU can not satisfy to all demands of on-board consumers of electric power in whole range of flight altitudes. The APU based on FC is more preferable but it design is more complex and have a big mass.

At present time the modern FC can not operate on liquid hydrocarbon fuel directly. So it is necessary to transfer liquid fuel into synthesis – gas (mixture of hydrogen and carbon monooxide). In the paper the usage of alternative non-oil fuel in APU have to be discussed. The ethanol as an alternative non-oil fuel is a good fuel for the APU.

The method of analytical hierarchy (Analytic Hierarchy Process – AHP) [11] is more suited for selection the optimal APU. This method is based on the idea that the efforts should be focused on the well-defined and pre-formulated decisions by comparing them only if the system consists of a lot of solutions. In the practice such approach is more preferable than the synthesis of uncertain solutions for system.

The general approach in the AHP framework includes the next steps:
- formation of the total goal (goals group) based on the objective of the system;
- formulation of the possible ways to achieve this goal;
- definition of the criteria for the different ways;
- separation of defined criteria according to their importance (hierarchy of criteria);
- selection of the optimal way in the previously formulated ways guided by the defined criteria starting from high-level criteria.

The total goal is the APU design which satisfy to all demands of on-board consumers in electric power in the range of flight altitudes.

As a possible variants of the APU design there are considered:
- gas turbine APU;

- hybrid APU based on solid oxide fuel cells (SOFC) on the aviation fuel (kerosene);
- hybrid APU based on SOFC on the alternative non-oil fuel (ethanol).

2 Analysis of the APU on SOFC and non-oil fuel

The APU mass has a great importance for aviation and is considered as the first level criterion for the optimal APU design. APU fuel consumption and air mass flow rate can be considered as another criterion of the first level.

Obviously it is not correct to compare the consumption of reaction components for the APU or the APU mass only. The weight impact of APU on aircraft is good criterion for the higher design level [4]. This criterion is defined as a sum of the APU mass and the fuel and other reactant mass which are used for the APU operation.

The aviation kerosene consumption is about 50% of the total consumption of all components which have to be reserved on a board of aircraft for the APU operation. The water is one of the most acceptable reactant for the APU [12, 13]. Of course the cost of water is significantly less than the cost of kerosene but the mass of water for synthesis–gas generation in the APU [12, 13] is approximately equal to the mass of kerosene. So the mass of water is an additional load on the aircraft. Therefore for the choice of the best APU design it is necessary to compare the weight impact of various APUs with taking into account the mass of all components which are required for the APU operation. Fig. 1 represents the typical time diagram of the dimensionless outlet power of the APU as $\bar{N} = N / N_{\max}$, where N is the outlet power, kW, N_{max} is the maximal outlet power.

Fig. 1 shows that the APU operate within one flight mission about 2 hours in total and it is possible to estimate the comparative weight impact of the APU on aircraft during this time.

There are considered two different types of SOFC for APU: planar SOFC (PC) and tubular SOFC. Fig. 2 represents the scheme of planar SOFC.

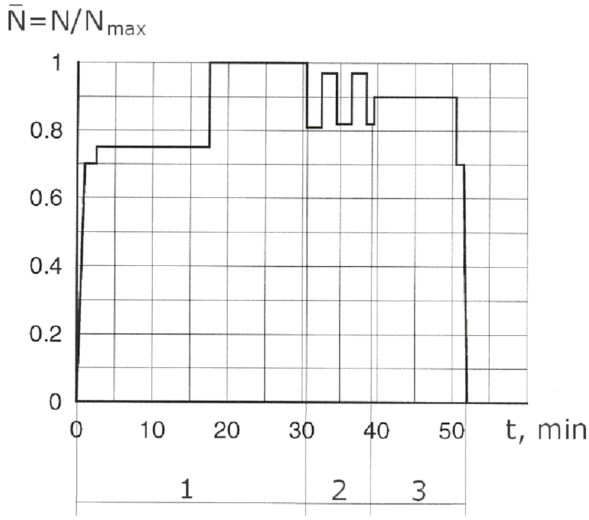

Fig. 1. The APU outlet power vs. time of taxi and take-off of airplane. 1 – ground taxi; 2 – start of two march gas turbine engines of aircraft; 3 – take-off and climbing.

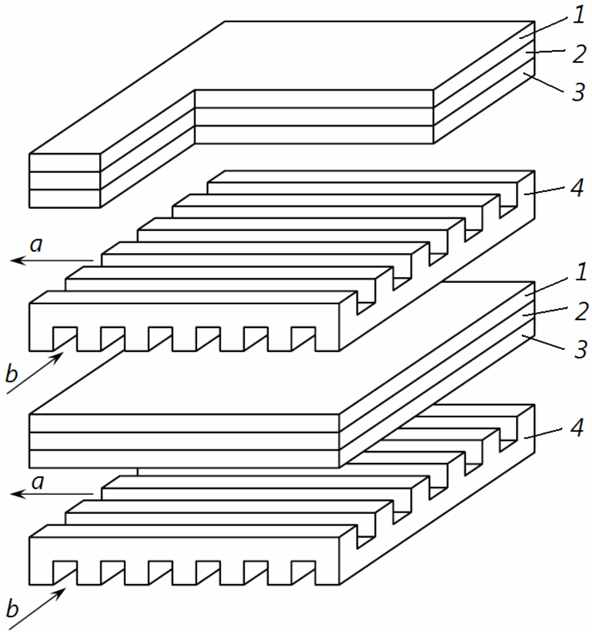

Fig. 2. The scheme of planar solid oxide fuel cell. 1 – anode; 2 – elecrolyte; 3 – cathode; 4 – interconnector; a) oxygen (air) channels; b) channels for synthesis–gas.

The PC has a more compact design based on the plate form of 100×100 mm [5]. One stack normally includes the 10 generating layers united by interconnectors. The interconnectors are used as the support elements of the stack. Usually the mass of such PC stack is appoximately 900g and maximal electric power about 500W on pure hydrogen and atmospheric air. The main PC disadvantage is the imperfection of sealing of fuel and air pipes inside the stack and a long start–up time (more than 3 hours) [6].

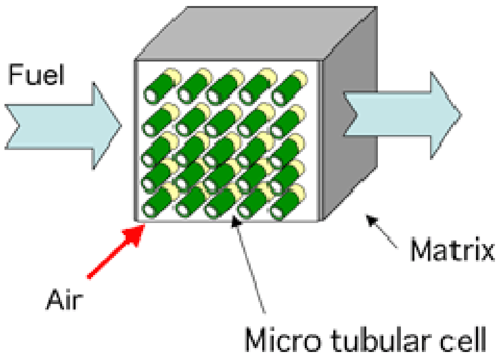

Fig. 3. The scheme of tubular solid oxide fuel cell.

The usage of the tubular solid oxide fuel microcell (MTC) improve the SOFC start characteristics [6, 8]. Fig. 3 represents the scheme of the MTC.

The tubular FC with the cross section diameter of 2 mm make possible to heat the SOFC up to temperature 900°C within 2–3 seconds [14]. The anode or cathode supported structure instead of the traditional electrolyte support structure make possible to increase the SOFC outlet power density. The sample of MTC represented in [6] has a value of specific power density about 1.5 W/cm^2. It is possible to create the stack with 4000 MTC in one unit. The typical cross section of such stack is represented at Fig. 4.

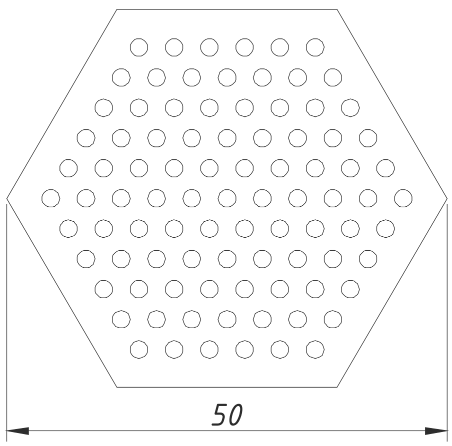

Fig 4. The cross section of the stack layer of tubular PC with 91 MTC.

One stack can include about 40 layers with MTC and produce an electric power of 800W. The tubular design has not a disadvantage of the pipes sealing in opposite of the PC design. The aviation APU on SOFC has to operate on the synthesis-gas as a kerosene reforming products.

There are tested three kerosene reforming technologies to produce the synthesis-gas from hydrocarbon fuels [8]: kerosene autothermal reforming and kerosene steam conversion and kerosene partial oxidation. The fuel steam conversion is a well-known process in chemical industry. A water steam reacts with hydrocarbons at the solid catalyst surface and produce H_2, CO and CO_2. This process produces hydrogen of high concentration but it is strongly endothermic process. The external source of heat energy is required for the kerosene steam conversion.

A fuel autothermal reforming is most complex process. At the first stage the fuel is decomposited at partial oxidation. As a result the unsaturated light hydrocarbons with CO and CO_2 and H_2O vapors are obtained in the reactor. At the second stage of the process the unsaturated light hydrocarbons react with a water steam on a solid catalyst with the same final products as at the fuel steam conversion. It is experimentally shown by author [10] that the concentration of H_2 in the fuel autothermal reforming is less then in the fuel steam conversion but the fuel autothermal reforming is a thermally neutral process. Hence the fuel autothermal reformer-reactor is light and compact and more preferable for mobile facilities on FC. The fuel steam conversion has a risk of carbonization of solid catalyst surface and stopping process at all. In opposite the usage of non-oil fuel (ethanol) steam conversion has not this imperfection.

The scheme of APU fuelled by the ethanol is shown on Fig. 5. The ethanol/water solution is fed the reactor-converter 2 where an endothermic conversion of ethanol into synthesis-gas takes place due to the heat generated by the fuel cells. The synthesis-gas enters in fuel cell battery 1. The burning process of fuel residual is completed in afterburner 3. The thermal energy of the produced gases is used to drive the turbine 4 for turn the air compressor 5 and the electric generator 6. The air compressor increases the pressure in the fuel cell battery. The generator 6 produces an additional electric energy.

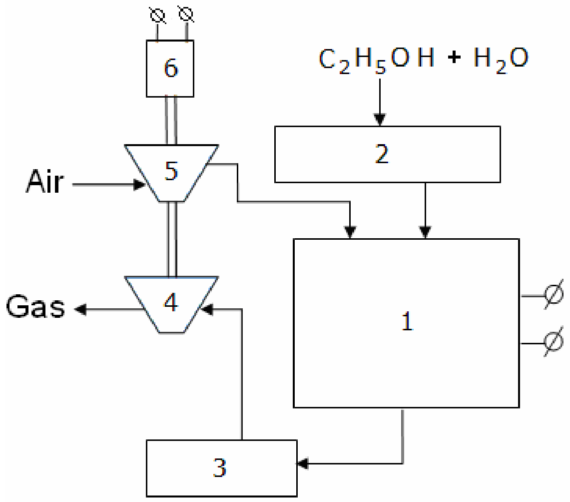

Fig. 5. Scheme of APU based on SOFC operating on the water-ethanol solution.
1 - fuel cell battery; 2 - reactor-converter; 3 - afterburner; 4 - gas turbine; 5 - air compressor; 6 - electric generator.

We compared the several types of APU: the gas turbine APU, the APU on PC and kerosene autothermal reforming, the APU on MTC and kerosene autothermal reforming and the APU on MTC and ethanol steam conversion.

It is obvious that the gas turbine APU which produce 350 kW at sea level can not produce the such power at high altitude. The air density at high altitude is significantly less then one at sea level and the APU air-intake can not caught air enough. So if it is necessary to switch on the APU at high altitudes we have to switch off a part of the on-board consumers of electric power and the goal of the APU selection will not be achieved. From other side if we can not switch off a part of the consumers we need more powerful and heavy gas turbine APU. It is not effective way because in case of normal mode operation a such APU will operate under a low efficiency. So we can consider two variants of gas turbine APU only. The first is the APU at power established on sea level only. And the second is the APU at power established in all range of flight altitudes.

For calculation the APU parameters the mathematical model of the APU is developed by the author. It includes the equations for thermodynamics: enthalpy and entropy, and the Gibbs free energy, the equation of heat balance in fuel cell battery, the equations for mass and volume of fuel cell battery and the gas-dynamic equations for turbocharge parameters.

The results of calculations are represented in Table for the advanced middle-range aircraft of MS–21 type. The demanded electric power of the APU is 350 kW in all range of flight altitudes.

Table

APU type	Gas turbine	Gas turbine	Planar SOFC, kerosene reforming	MTC, kerosene reforming	MTC, ethanol steam conversion
Goal - 350 kW at all range of flight altitudes	-	+	+	+	+
Electric power of SOFC battery, kW	-	-	270	280	300
Electric power of gas turbine unit at sea level, kW	350	1500	80	70	50
Effective efficiency, %	22.0	10.0 (for generation 350 kW at sea level)	47.0	51.0	69.0
Fuel consumption, g/s	45.0	87.0	17.3	16.0	19.0 (for 100% ethanol)
Water consumption, g/s	-	-	19.0	17.5	7.5
Air consumption, kg/s	2.6	5.8 (for generation 350 kW at sea level)	0.47	0.4	0.3
Mass of SOFC battery, kg	-	-	270.0	200.0	28.0
Mass of the gas turbine unit, kg	180.0	830.0	40.0	34.0	24.0
Mass of electric generator, kg	172.0	172.0 (for generation 350 kW at sea level)	40.0	34.0	25.0
Total mass of APU, kg	352.0	1002.0	437.0	287.0	283.0
Weight impact for 2 hours APU operation in nominal mode	676.0	1630.0	698.0	527.0	473.0

It is shown that the APU on MTC reduces the APU weight impact on aircraft in 1,4 times in comparison with the gas turbine APU. The APU on planar SOFC has the same weight impact on aircraft as the gas turbine APU. But gas turbine APU can not supply the on-board consumers of electric power in all range of flight altitudes. If the gas turbine APU will be created and can reach this goal the weight impact of such APU will be increased up to 1600 kg. Relatively this big gas turbine APU, the APU on planar SOFC reduces the weight impact more than 2 times and APU with MTC reduces the weight impact more than 3 times. The minimal weight impact on aircraft will be given of the APU on MTC which operate on the products of ethanol steam conversion. Such APU will have maximal high efficiency (69%) and minimal air mass flow rate (0.3 kg/s).

It is important that all APUs on fuel cells have a low air consumption. It makes possible to use the waste air from the aircraft cabin for supplying the APU. Hence the APU on fuel cells can give the nominal electric power in all range of flight altitudes. This property is impossible for gas turbine APU because a big value of air mass flow rate prohibited such combination. The APU on fuel cell reduce the APU fuel consumption too. For the APU on kerosene reforming the fuel mass is reduced 2,8 times in comparison the gas turbine APU, and for APU on ethanol steam conversion – 2,4 times. Nevertheless the weight impact from APU on ethanol will be minimal among all APU considered (473 kg).

3 Conclusion

1. The APU design on MTC and ethanol steam reforming has a minimal weight impact on the advanced middle-ranged aircraft MS-21 type.
2. The difference between the weight impact of APU on kerosene autothermal reforming and the APU on ethanol steam reforming is small and not exceed 11%.
3. The planar SOFC significantly increases the APU weight impact on aircraft but allows using the waste air from aircraft cabin. The APU on planar SOFC can satisfy all requirements of on-board consumers in electrical power at all flight altitudes.

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