Advanced Catalytic Technologies and Possibilities of Fuel Cell Application in Aviation

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Abstract

The modern civil aviation has tends to change conventional hydraulic and pneumatic drives and controls with electrical ones. This trend is expessing into the “All Electrical Aircraft” concept in which all auxiliary power for aircraft will be based on electricity. So the more effective and powerful auxiliary power unit (APU) for producing electrical power wanted for future aircrafts. One of most attractive variants - is using fuel cell in APU. Such APU could offer high efficiency, low noise and excellent ecological characteristics. At present time a fuel cell cannot operate on hydrocarbon fuels directly. For using in fuel cells the hydrocarbon fuel shall be transformed in hydrogen or synthesis - gas – mixture of carbon monooxide and hydrogen. But traditional process of synthesis – gas generation is needed in water consumption as additional reagent. It is not good for aviation because a lot of external reactant shall be provide on board of aircraft.

In case of using solid oxide fuel cell (SOFC) a new catalytical technologies make possible more progressive process - preferential oxidation of aviation kerosene in synthesis-gas without water with using only atmosperic air. These create possibility of using SOFC in aircraft main engines (ME) too. The paper contains results of mathematical modelling of the mass and dimension characteristics of advanced aviation APU and ME with SOFC in comparison with traditional gas turbine engines. The obtained results show that advanced APU and ME with SOFC can be more preferable for aviation than traditional gas turbine engines.

1. Introduction

Now an opportunity of "More Electric Aircraft” development is discussed as a one of more perspective ways for future civil aviation. In future aircraft the electrical power will replace other sources including mechanic, pneumatic and hydraulic power. A power consumption by onboard systems is increased considerably by transfering to "All Electrical Aircraft" in which all auxiliary power will be based on electricity [1]. Demanded level of electric power consumption in such plane is estimated from 500 kW up to 1500 kW. So more effective and powerful auxiliary power unit (APU) wanted for aviation.

It is universally recognized that the main way for upgrade an APU is using battery of fuel cells as a source of electrical power. There is two ways for realize this idea: it is using Polymer Electrolyte Membrane fuel cells (also Proton Exchange Membrane fuel cells or PEM) and using Solid Oxides fuel cells (SOFC).

A SOFC technology uses ceramic electrolyte in which negative ions of oxygen exchanges from cathode to anode [2]. Diffusion process of oxygen ions arises voltage difference between anode and cathode. An ion conductivity of keramic electrolyte is very small at normal temperature. As a result, an optimal operating temperature of SOFC is equal 800–1000^{0}C. The best fuel for SOFC is a pure hydrogen, but SOFC can use carbon oxide as a fuel. These circumstances make more easy problem of fuel cells operating on liquid hydrocarbon fuel and can give additional gain in thermal efficiency of power unit. In case of using liquid Jet fuel for supplying power unit with fuel cells, it is necessary to produce hydrogen from liquid hydrocarbon fuel. The special process – autothermal reforming (ATR process or ATR) has been proposed for synthesis - gas generation [3].

2. Experimental researches of operating process in fuel cell battery

An ATR process - it is a complex, two stage process. At first stage the reaction of particular oxidation is used as source of light olefine hydrocarbons from initial liquid fuel, and at the second stage – the water steam conversion of light hydrocarbon compositions on special solid catalyst is used for obtaining synthesis - gas with significant hydrogen concentration. The important distinction of this process – additional water consumption for hydrogen production.

It is experimentally shown, that the steam conversion [4] may be possible only when abundance quantum steam injected in reaction zone. In other case the hard carbon deposits are covered active surface of catalyst. So in case of using traditional catalysts, which used in chemical industry, the mass flow rate of water shall be exceed mass flow rate of fuel in three – five times. A high water mass flow rate make additional weight impact on the aircraft and decrease possibility APU based on fuel cell technology.

A significant water economy can be obtained by using new catalyst technology based on using catalytical porous membraines. The porous membraines have on 1cm^2 membraine surface a lot of microchannels which penetrate membraine body. Microchannels have internal communications, because membraine creates with communicating pores.

Internal surface of the pores are covered by small catalyst centers, created solid catalyst materials in order to accelerate chemical reactions of steam conversion. A complexes of rare metals Pt , Co , Ce are used as a catalyst. Methods of nanotechnology are used for nanoparticles location on internal surfaces of the membraine microchannels [5]. In this case a porous ceramic medium plays role of the big chemical reactor and nanosized catalytic centers are placed in internal surface of communicating pores. There are $10^7...10^9$ catalytic channels on 1 cm^2 of such membraine with ~ 10^6 catalytic centers in one channel. Membraine is represented as a composition a huge number of “nanoreactors”.

Performing reactions in nanocatalytic system gives significant advantages. There is no any additional reaction products in reaction. In nanocatalytical membraines create only main, useful reaction products. In these membranes reaction go up to the end without exceeding steam. The stoichiometric relation between steam and hydrocarbon gases is enough for chemical reaction.

The special laboratory test facility has been created for investigation kerosene reforming to synthesis–gas for SOFC feeding. The scheme of test facility is shown of Fig. 1. The facility contains the reactors (5) and (6) for two separate stages of the autothermal reforming. Micropumps (2) supply the undecane ($C_{11}H_{24}$) and water to the first reactor (5). The undecane has been used as analogous Jet A-1 fuel in these experiments. This reactor contains inert porous filler and located in the electric furnace providing the heating of porous medium up to temperatures 780–800°C. The excess air factor - α in air – fuel mixture maintained about 0,2 (The excess air factor $\alpha=1$ correlates stoichiometric ratio). The oxidation process was initiated when temperature level in air –fuel mixture risen up to 270°C. The pressure in chemical reactors (5) was changed in 0,1 – 0,5 MPa interval. The formed gases come to second reactor (6) for a steam conversion in the nanocatalytical porous membrain. Further the synthesis–gas comes to the SOFC (13) which operating with the external electric load. The SOFC is placed in separate electric heater. The samples of synthesis–gas is periodically performed for the control of its chemical composition.

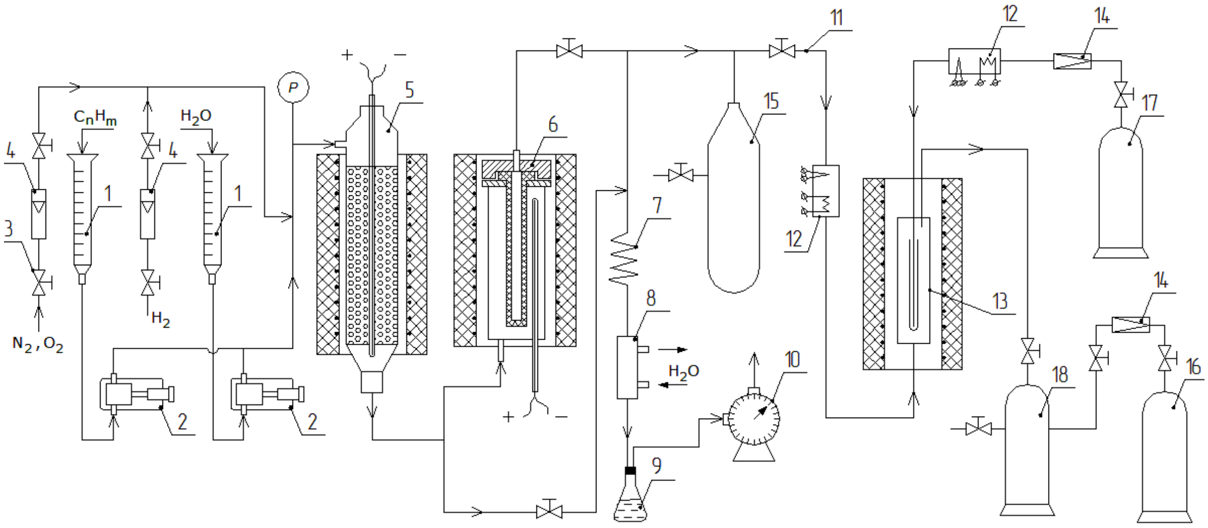

Fig 1. Scheme of experimental facility.

1 – metric volume for fuel and water; 2 - dosing micropump; 3 – air ventile; 4 – volume gas meter; 5- reactor for partial fuel oxydation; 6 - reactor for steam conversion; 7- air cooler; 8- water cooler; 9 - volume vessel for liquid fraction; 10 – gas meter; 11- ventile; 12- air volume flow meter; 13 - SOFC; 14 – gas reductor; 15 – inside gas balloon; 16 – high pressure nitrogen balloon; 17- high pressure air balloon; 18 – common gas balloon for wasted gases.

Fig. 2 represents typical composition of conversion reaction products in reactor (6). The composition is obtained at residence time of reacting mixture on the first and second stages of 0.4 and 0.6 sec, respectively.

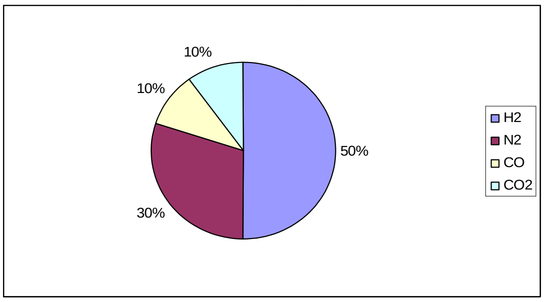

Fig. 2: Partial pressures of reaction products ATR of undecane.

The argone, which consists in air, is not included in diagram, because its concentration in ATR products is not more 0.3% by volume. Concentrations of residual methane and high molecular hydrocarbons compositions are not included too. The concentration of methane no more 0.1% by volume and concentrations of high molecular hydrocarbons less then 0.01%.

Fig. 3 represents volt-ampere and power characteristic of the SOFC during its operating on the synthesis–gas and on the hydrogen.

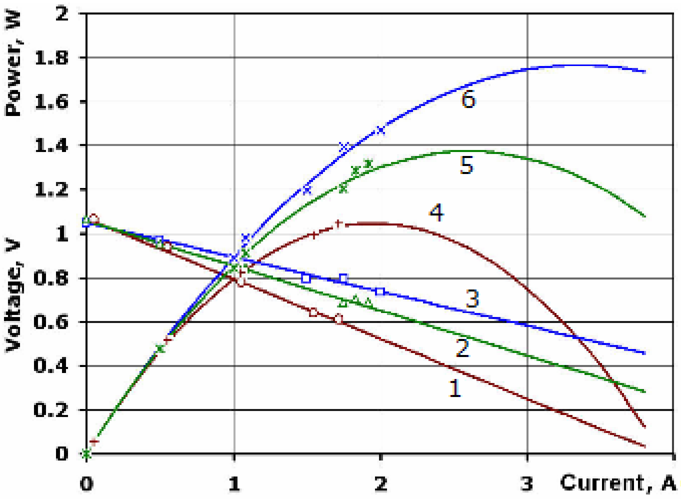

Fig. 3. Volt-ampere characteristics (1-3) and power (4-6) of the SOFC sample.
Hydrogen: 1, 4 - T_{op} = 835°C; 3, 6 - T_{op} = 950°C. Synthesis–gas: 2, 5 - T_{op} = 950°C.

Transition from the hydrogen to the synthesis–gas leads to reduction value of power maximum - $P^0_{sp\max}$ no more than on 20 %. It should be noted that $P^0_{sp\max}$ is determined as a maximum of P^0_{sp} curve vs. density of electric current generated by SOFC.

In the above described experiments a water was used as an additional reagent for the synthesis–gas generation. Water consumption is not more than 1 kg on 1 kg of fuel. The experiments for synthesis–gas generation without water has been performed too. For this purpose the products of incomplete oxidation of the initial fuel containing water vapour and CO_2 have been passed through nanocatalytic membrane. For producing water vapors and CO_2 an increased quantity of air is used in reactor (5). The excess air factor - α in these experiments is 0.48. The fig 4 is represented the synthesis – gas composition which was obtained in discribed experiments.

The produced synthesis–gas includes: $N_2 = 64$ %; $CO = 14$ %; $H_2 = 12$ %; $CO_2 = 9,25$ %; $Ar = 0,75$ % by partial pressure. The process looks as more chemically active hydrogen (H_2) did not react with oxygen of air, but less active carbon reacts with O_2 and forming *CO* as a product of preferential oxidation of carbon material.

As product of reaction, the obtained synthesis–gas can be used in a fuel cells. Distinctive feature of process is the generation of synthesis–gas without water. It allows consider an application of SOFC not only in auxiliary power unit but in march engines of advanced aircrafts too.

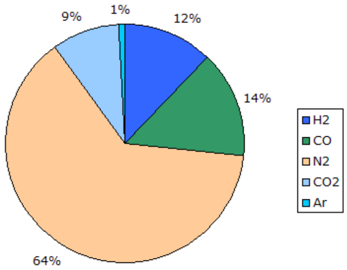

Fig. 4. Partial pressures of reaction products process of selective oxidation of undecane.

3. Opportunities of new aviation technology

A SOFC using in aviation applications are considered as possible onboard source of electric energy. Mass and size parameters are governing factors for aviation power units. Methods of estimation main energetic and mass parameters for gas turbine power units and fuel cell power units are well known and they are represented in modern technical literature [2], [6 –8].

A new power unit can be used in aviation only if it’s specific power will be comparable with specific power lewer of gas-turbine aviation power unit (APU). It is about 2.8 kWt/kg [9], that approximately in 30 times higher than values of SOFC developed for ground power programs, as SECA. Therefore, application of fuel cell in aircrafts requires development of a new SOFC with higher energetic characteristics.

Fig. 5 represents a SOFC battery mass with output electric power 300 kWt vs. maximum SOFC surface power density. The computation accounts that the surface power density for SOFC depends on pressure reactant substances as

$$P_{sp\max} = P^0_{sp\max} \cdot \left(\frac{p}{p_0} \right)^n , \tag{1}$$

where p_0 is atmospheric pressure; n is a degree factor of accounting pressure effect.

Fig. 5 shows that the mass of fuel cell battery has high correlation with SOFC maximum surface power density.

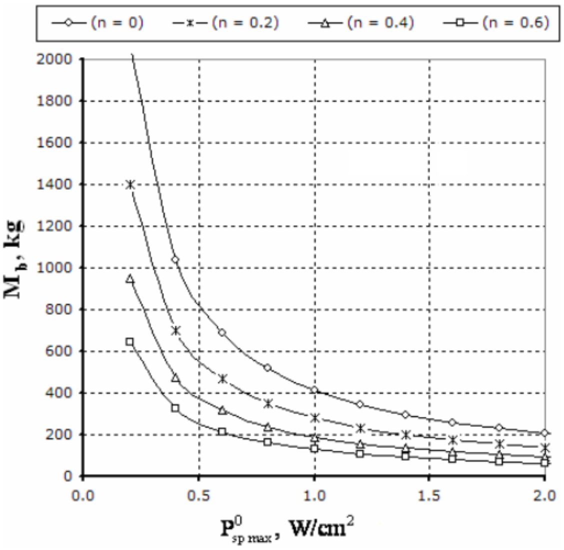

Fig. 5 Mass of 300 kW SOFC battery vs. maximum surface power density

Fig 5 shows that SOFC used at present time in ground power stations are not good for aviation. The surface power density of these SOFC are very low (about 0.1 W/cm^2) and mass of construction exceed any possible limits.

In order to reduce the mass of construction, SOFC microcells are represented by AIST Institute (Japan) [10]. Application of such microcells makes possible significantly reducing the design mass fuel cell battery.

Original design of “thin-wall” SOFC is produced by Institute of Electrophysic in Russia (Ekaterinburg). The “thin-wall” SOFC has high volt-ampere characteristic and small weight [11]. Assembling the fuel cells in compact block allow to develop a fuel cell battery with acceptable mass characteristics for aviation (Figs.6).

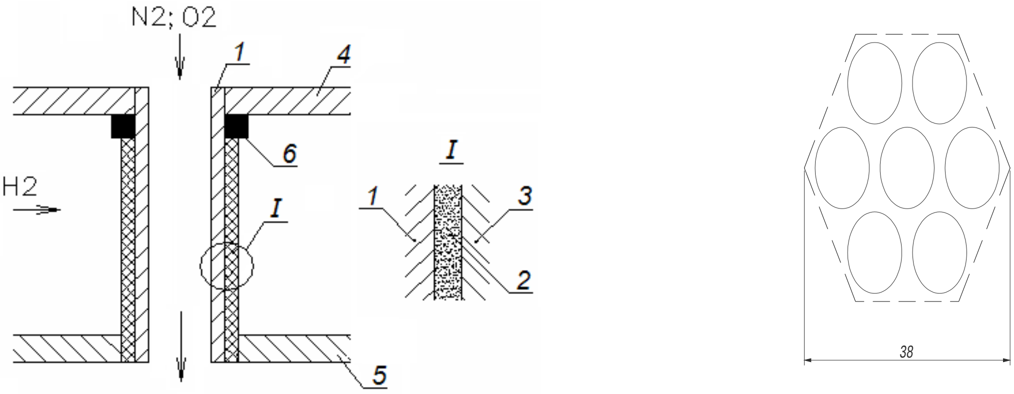

Fig. 6 “Thin-wall” SOFC and their location in compact block. 1 – cell base (anode); 2 - electrolyte; 3 - cathode; 4 - anode plate; 5 - cathode plate; 6 - isolator.

To show advantages a new power system, the comparative estimation of main parameters perspective APU on the basis of “Thin-wall” SOFC and traditional turbine APU system for short - middle range aircraft (SMRA) has been performed. The energetic system SMRA MC -21 type consists of gas turbine APU with outlet electric power about 350 kWt and two electric generators, installed on two main engines with total electric power ~ 700 kWt. The modern gas turbine APU TA 18 -200 can be discussed as real prototype gas turbine APU for SMRA. APU operates when aircraft stay on the ground and main engines are stop. During flight, when main engines are in action, APU does not operate. Table 1 consists main parameters for three APU variants. First – TA 18 – 200 APU, second – perspective APU with “Thin wall” SOFC and synthesis – gas generation in ATR process with using additional water and third – APU with synthesis – gas generation in preferential oxidation process.

Table 1 shows that the gas turbine APU creates approximately in two times more weight impact in comparison with perspective SOFC systems.

Table 1

Main parameters for modern gas turbine APU and perspective APU with SOFC and different systems of synthesis-gas generation. Demanded APU electric power – 350kW under normal conditions.

Parameter	Gas turbine APU (TA -18 -200)	APU with autothermal reforming	APU with preferable oxidation process
APU Mass with electrogenerator, kg	365.0	225.0	270.0
Reactant mass flow rate, kg/h			
kerosene	222.0	63.7	82.8
water	-	55.4	-
Air mass flow rate, kg/s	2.4	0.53	0.93
Electric Power of fuel cell battery, kW	-	267.0	238.0
Mass of fuel cell battery, kg	-	122.0	107.0
Mass of electrogenerator, kg	182.0	47.0	67.0
Effeciency, %	13.0	46.0	35.0
Aircraft weight impact (operating during 2 hours under normal power), kg	809.0	463.0	434.0

The most preferable system from fuel consumption point of view is APU with generation synthesis – gas in ATR - process. In case of using preferable oxidation process the fuel consumption increased in 1.3 times.

Significant gain in APU weight impact in case SOFC system, make to discuss opportinity of using SOFC in aircraft main engines. The scheme of hypothetical "electric" turbofan engine for airplane is represented on fig 7. The main distinction "electric" engine is avaibility the fuel cell battery (2) with reformer (3) as addition energy performed unit to combustion chamber. The fuel cell battery directly produces electric power from fuel energy. This power is using for creating trust by turning main trust fan with electric motor. The free energy of gas turbine in turbofan is used for turning additional trust fan too. So two fans create trust force in electric turbofan engine. Because all fuel in fuel cell battery operating process cannot be utilized, the fuel remaines are burnt in afterburner (3). So in case of "electric" turbofan the combustion chamber in really is afterburner.

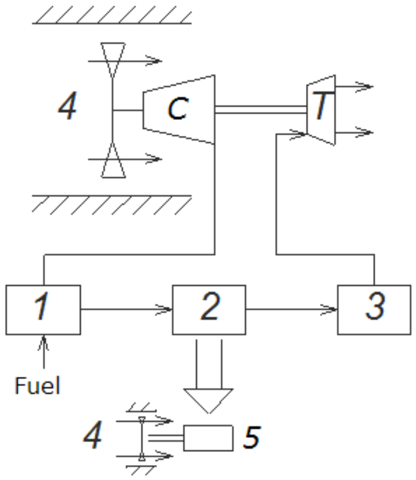

Fig 7. The scheme of turbofan engine with fuel cell battery.1 - reformer; 2- fuel cell battery; 3 – afterburner; 4 – fan; 5 – electric motor.

For establish advantages of new type aviation engine, the compare main characteristics of airplane with "electric" turbofan engine and traditional turbofan is performed for regional distance aircraft. As good sample of regional aircraft for comparing, the AN -12 airplane with turboprop engines АИ -20. AN – 12 is a regional cargo airliner. External views of airplane is represented on fig 8.

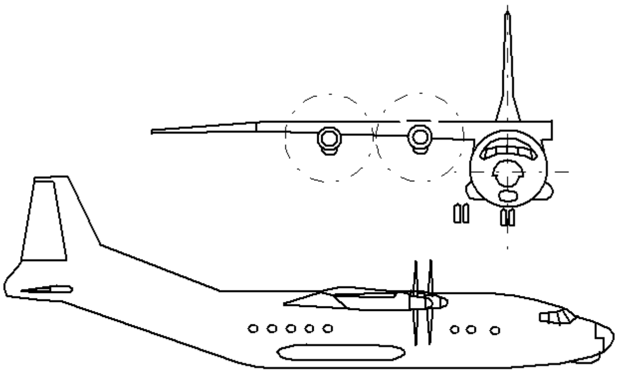

Fig 8. The AN – 12 regional cargo airplane with АИ -20 tyrboprop engines

4. System analysis new type of engines

Connections between an air - breathing engine and the aircraft should be considered from point of view of aircraft level criteria. Therefore the system «flight vehicle – engine – fuel» (FVEF- system) is considered and described by the imitative mathematical model (IMM) [12].

New types of air – breathing engines can change the aircraft performances not only, but direct to essential influence on its operation also.

The IMM allows to compute the thrust-economical and size-mass parameters of aircraft engine and geometrical, aerodynamic, volumetric-mass characteristics and trajectory parameters of flight vehicle (FV) on a typical profile of flight and also to compute the influence of fuel properties on them [12, 13].

The FVEF – system IMM includes the next mathematical models (MM):

- MM for computation of geometrical, aerodynamic, volumetric-mass and aircraft flight-performance characteristics;
- MM for computation of velocity-altitude, throttle and size-mass characteristics of various engines including the engines with FC;
- MM for fuel properties.

New MM of aircraft engine with SOFC is included into IMM. As a result it is possible to form a preliminary view of “electric” engine and to determine a control system of its operating modes.

In presented MM the aircraft engine has reformer used only preferential oxidation process. The preliminary estimations have been shown that ATR process with water have not significal gains in comparison with traditional gas turbine variant. It is obvious that the kerosene as fuel for preferatial oxidation process has essential disadvantage: only 60% of initial energy of fuel comes to fuel cell battery for transformation into electric energy. The others 40% of energy are generated in reformer during the synthesis–gas formation. Therefore alternative fuels able to transform the synthesis–gas at smaller losses in reformer seems to be more preferable for engines with SOFC. Liquefied natural gas (LNG) and aviation condensed fuel (ACF) from gas can be used as alternative fuels.

LNG can be transformed to the synthesis–gas with loss of 25% from initial heat of combustion. Losses at transformation of ACF will be approximately the same as well as for kerosene. But density of ACF is less than kerosene. So more volume of fuel can be placed in aircraft tanks without breaking restriction maximum start mass.

In this report the initial scheme of the regional aircraft (AN -12) with turboprop engines (TPE) on aviation kerosene is chosen as variant 1. The variants 2, 3 and 4 are the modernization of variant 1 by using new engine and new fuels: variant 2 corresponds TPE - FC on aviation kerosene, variant 3 – TPE - FC on LNG and variant 4 – TPE - FC on ACF.

According to data represented in [11], the value $Đ^{0}_{sp\ \max}$ is equal 0.7 W/cm^2, but this value is reduced on 20% for SOFC on synthesis–gas generated from kerosene (Fig. 3). So, for SOFC on synthesis–gas the value $Đ^{0}_{sp\ \max}$ is equal 0.56 W/cm^2 in variants 2 - 4. The value of heat combustion lost at kerosene transformation to synthesis–gas $\delta Í_{è}$ is equal 0.4 at $H_u = 42,9$ MJ/kg and it is assumed that the resistances ratio $K_R = 2$.

The typical profile of flight represents the take-off with given maximal aircraft take-off weight of 61 ton and useful loading of 20 ton, the ascent of 6000 m and the cruise flight at Mach number M = 0.48. After decrease of the fuel mass on 20% from the take-off fuel mass (an aeronavigation reserve), the descending and landing are carried out.

Maximal possible flight range at cargo transportation of 20 ton at the fixed maximal take-off mass of the aircraft (61 ton) is considered as criteria of efficiency of the variants.

5. Results of analysis

Table 2 represents mass of aircrafts and engine mass parameters for variants 1 - 4.

Transition from variant 1 to variant 2 gives increase of the engine mass on 1640 kg. Accordingly the fuel mass reduce from 6000 kg down to 4360 kg. The TPE - FC operating on ACF is easier and the fuel mass filled in the aircraft is 4560 kg. If LNG are used as a fuel the mass of external cryogenic fuel tank (CFT) in addition increases the engine mass by 350 kg. Therefore in variant 3 a mass of the TPE - FC is 6150 kg.

Deterioration of the aircraft aerodynamic quality because of the external CFT is 3% at variant 3. In variant 4 the ACF fuel is used in a liquid phase in all range of altitudes and speeds of flight. A fuel consumption in the TPE - FC is much less than in the TPE due to higher efficiency.

Therefore at transition on the TPE - FC fuel efficiency improves and flight range increases despite of reduction of onboard mass fuel.

Despite of smaller initial amount of fuel in variants 2, 3 and 4 the fuel consumption appear so low that it allow to increase the flight range of aircraft. In case of using LNG the flight range of aircraft increase in 2.2 times in comparison with initial variant on turboprop engines. In case of using kerocene and ACF increasing flight range will be 1.8 and 1.9 accordingly.

The initial data used at the engine computation are confirmed by results of researches of the authors in the field of modern SOFC on different fuels, however they concern only to stationary conditions of operation that leads to a little bit optimistic estimations for the new engine. Therefore the further researches are necessary for more objective estimation of parameters of aircrafts on engines with SOFC on different fuels.

Table 2

Main parameters for turboprop “АИ -20” and perspective “electric” engines with SOFC on different fuels.

Variant	1	2	3	4
Fuel	kerosene	kerosene	LNG	ACF
M_{engine}, kg	1080.0	1190.0	1100.0	1180.0
N_B, kW (Electric Power of fuel cell battery)	-	1200.0	1390.0	1296.0
M_B, kg (Mass of fuel cell battery)	-	670.0	724.0	722.0
M_{EM}, kg (Mass of electromotor)	-	300.0	350.0	330.0
M_{CFT}, kg (Mass of criogenic fuel tank)	–	–	350.0	–
M_{AE}, kg (Summary mass of turboprop engines)	4320.0	5960.0	6150.0	5760.0
M_{fuel}, kg (Fuel mass in aircraft tanks with aeronavigation fuel reserve)	6000.0	4360.0	4170.0	4560.0
C_{SP}, kg /(kW·h) (Specific fuel consumption)	0.46	0.182	0.136	0.166
η_{EF} , %, (Engine efficiency on cruising operation mode)	17.0	45.5	52.0	47.8
Flight range, km	635	1165	1417	1185
Fuel efficiency, g/T·km	377	149	117	144

6. Summary

1. Aviation APU with the “Thin wall” SOFC has acceptable mass characteristics for aviation.
2. Weight impact on aircraft from APU with SOFC can be reduced in 2 times as compared with the weight impact of the traditional gas turbine APU. Furthermore APU with the SOFC uses the same aviation fuel (with water addition) as aircraft main engines.
3. The opportunity of aviation kerosene reforming without water into synthesis–gas is experimentally proved.
4. The new scheme of the turbofan engine with the SOFC battery (TFE-FC) on the synthesis–gas produced from onboard aviation kerosene is offered.

5. The flight characteristics of the regional aircrafts with SOFC turboprop engine (TPE-FC) on the synthesis–gas produced from different fuels: aviation kerosene, liquefied natural gas (LNG) and aviation condensed fuel (ACF) are the following:
    - TPE-FC on aviation kerosene allows to increase flight range of FV on 80%, and to increase fuel efficiency in 2.5 times;
    - TPE-FC on ACF allows to increase flight range of FV on 90%, and to improve fuel efficiency in 2.6 times;
    - TPE-FC on LNG allows to increase flight range of FV on 120%, and to improve fuel efficiency in 3.2 times.

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