TRANSPORT AIRCRAFT WITH HIGH FUEL EFFICIENCY WITH "ELEC-TROCHEMICAL" GAS TURBINE ENGINE BASED ON SOFC ICAS 2014

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Abstract

The report focuses on the analysis of the possibility of using solid oxide fuel cells (SOFC) in the propulsion engines of transport aircraft. The fuel efficiency is examined as efficiency factor by comparison of traditional turbofan and hybrid engines based on SOFC.

1 Introduction

At present time the main tasks of the civil aviation development are the cost reduction of the transportation of goods, the increase of flight range, the improvement of environmental performances and first of all the reduction of CO2 emission. The traditional turbofan engines (TFE) on aviation kerosene do not allow solving these problems noticeably.

One way of further improvement of the aviation engine efficiency is a transition to a hybrid TFE based on electrochemical generator with solid oxide fuel cells (SOFC) [2], as well as the use of alternative fuels such as liquid natural gas (LNG) and hydrogen. The SOFC usage is one of the most promising solutions, because it provides a high efficiency and high environmental performances.

The goal of this paper is a performances comparison of traditional TFE and hybrid TFE based on SOFC at different fuels. The fuel efficiency (fuel consumption for transportation of 1 ton of useful load per 1 km) is selected as efficiency criterion.

2 The scheme of the hybrid TFE and system analysis

The schema of a new hybrid TFE [1] is presented on the fig. 1. In contrast to traditional TFE the combustion chamber (3) is supplemented with a SOFC battery (1). The engine is provided with a remote fan 8 driven by a motor (4). The motor is located in the cowling and powered by electrical energy from the SOFC battery (1). The SOFC battery is located in the cowling near the TFE and generates a constant electric current due to electrochemical reactions with a direct conversion of chemical energy into electrical. The hydrocarbon fuel is supplied to the reformer (2) to be converted into a synthesis gas before being fed to the battery.

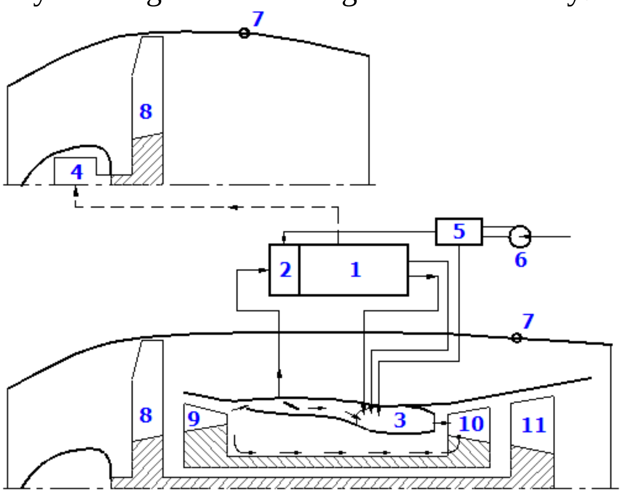

Fig. 1. The scheme of hybrid engine with the SOFC battery and the remote thrust fan. 1 - SOFC battery, 2 - Reformer, 3 - Burner, 4 - Electric motor, 5 - Fuel flow controller, 6 - Fuel pump, 7 - Nozzle of low-pressure contour, 8 - Remote thrust fan, 9 - High pressure compressor, 10 - High pressure turbine, 11 - Low pressure turbine.

At transition to a new scheme the communication between aviation engine and the aircraft should be considered with taking into account the criteria of the aircraft level. Therefore in the work the "aircraft-engine-fuel" (A-E-F) system is considered. This system is described by the imitation model (IM) (fig. 2).

IM allows compute thrust-economical, size-mass characteristics of a new engine as well as geometrical, aerodynamic, volumetric-mass and trajectory characteristics on typical flight profiles and also to calculate the influence of fuel properties to them [3,4].

IM of "A-E-F" system includes the following mathematical models (MM): MM of aircraft for estimation of geometrical, aerodynamic, volumetric-mass and flight performances; MM of engine for design and estimation of altitude-velocity, throttle and size-mass characteristics of different engine schemas including engines on fuel cells; MM of fuel performances; calculation unit for estimation of performance criteria (PC) of the system "A-E-F".

MM of engine includes a new MM of SOFC and makes it possible to obtain a preliminary appearance of engine with SOFC battery as well as to determine an engine control system taking into account joint work of engine elements at off-design conditions.

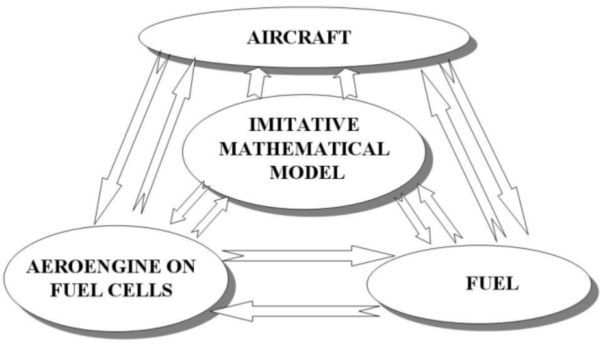

Fig. 2. Relationship of Imitation model with "A-E-F" elements.

MM of SOFC battery integrated into MM of aviation engine expands capabilities of the study of the influence of various engine schemas on the "A-E-F" system. It is possible to analyze the following criteria: fuel efficiency, flight range, takeoff mass, the flight hour cost, emission of harmful substances and etc. The "aircraft", "engine" and "fuel" aspects of design are combined in the IM. The interaction with multiparameteric optimization is organized and make it is possible to optimize any parameter of aircraft, engine and fuel.

During calculation of the range and other aircraft flight characteristics the system of ordinary differential equations of the first order is integrated which describe the motion of the aircraft mass center in the trajectory coordinate system. The aerodynamic and volumetric-mass characteristics of the aircraft as well as the altitude speed and size-mass characteristics of the engine obtained in the previous stages of calculation are used as initial data for flight performance calculation.

In order to verify the IM the calculations and comparative estimations are performed for some series engines on aviation kerosene (SaM-146, PS-90A, D-30KP, D-18T, D-36) and aircrafts (SSJ-100, Tu-204, Il-76, An-124). The error of thrust and specific fuel consumption is not more than 5%. The error of aerodynamic, volumetric-mass and flight characteristics (depending on the aircraft scheme and the flight Mach number) is not more than 10%, which is acceptable for preliminary design of aircraft with new engine schemes on alternative fuels.

3 Estimation of the fuel efficiency within cruise at a fixed flight range and take-off mass

Consider cruise (excluding take-off, climb and landing) with Mach 0.78 (828 km / h) at the same flight range of 4 variants of advanced medium-range aircraft with airframe mass of 30 t and thrust of 2400 kgf. In the 1st variant the advanced TFE of traditional scheme is used, which should have a mass of about 1170 kg [5] and specific fuel consumption (kerosene) C_R =0.52 kg / (kgf×hour) [5]. In other variants a hybrid TFE based on SOFC is used with different parameter of K_R (the meaning of K_R is described below). The flight range had to be specified and to be the same for all variants of aircraft. For the specified flight range the take-off mass of all aircraft variants had to be the same and had to be determined using the 1st variant of the aircraft, in which the mass of the useful load had always to be 18 t. The useful load for other variants of aircraft is determined from the condition to ensure the same take-off mass as in the 1st variant.

One of the key parameters that can be specified in the design of SOFC batteries for hybrid TFE is the ratio of the resistance of the external circuit to the internal resistance of the battery K_R [6]. The greater the value of this parameter is taken in the design of hybrid TFE, the smaller the specific consumption of the engine will be, but the greater the mass of batteries SOFC will be. For $K_R = 2$ and the thrust of 1200 kgf hybrid TFE will have a mass of 2064 kg [6] and the specific fuel consumption C_R = 0.4 kg/(kgf×h) [6]. In this section, the variants of aircraft with a hybrid engines differ only in the value of K_R. In all variants fuel is aviation kerosene.

Aircraft engines are characterized by such parameter as the weight load on the plane. The weight load is the sum of the mass of the engine and the mass of the fuel consumed during the flight. Fig. 3 shows the influence of the flight range on the weight load of conventional TFE and hybrid TFE based on SOFC battery with 2.5 kWh/kg [6]. Beginning with the 6000 km flight range the hybrid TFE does not concede to the traditional TFE.

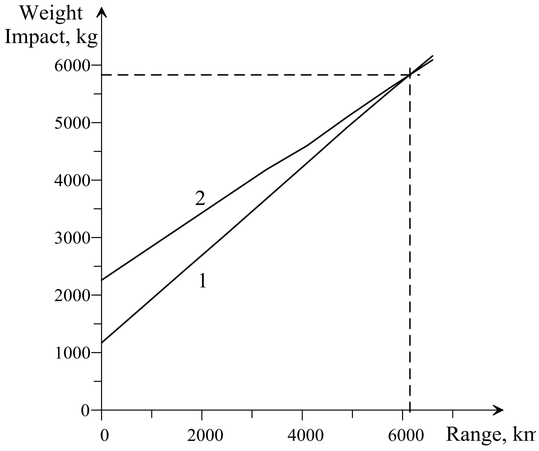

Fig 3 Weight load on the aircraft as a function of the flight range for conventional TFE (1) and hybrid TFE (2) based on SOFC battery with 2.5 kW/kg and K_R = 2. Fuel is aviation kerosene.

Despite the fact that the hybrid TFE in the flight range later than 6000 km inferior to the traditional TFE on the weight load, however, provides a better value of the fuel consumption in the transport of 1 t per 1 km (fuel efficiency). Table 1 shows the results of estimation of the fuel efficiency in the cruise for different versions of aircraft.

Table 1. Estimation of aircraft fuel efficiency with different engines at a fixed take-off mass and flight range.

Engine	Flight Range, km	Takeoff mass, kg	Engine Mass, кг	Useful Mass, кг	Required mass of fuel, kg	Specific fuel consumption, кг/(час.кгс)	Fuel efficiency, g/(t×km)	Eco-no-my
Traditional TFE	1656	52836	1170	18000	2496	0.52	83.7	
Hybrid TFE (Kp = 2)	1656	52836	2064	16788	1920	0.4	69.1	18%
Hybrid TFE (Kp = 3)	1656	52836	2274	16425.6	1862.4	0.388	68.5	18%
Hybrid TFE (Kp = 4)	1656	52836	2510	15982.4	1833.6	0.382	69.3	17%
Traditional TFE	4140	56580	1170	18000	6240	0.52	83.7	
Hybrid TFE (Kp = 2)	4140	56580	2064	17652	4800	0.4	65.7	22%
Hybrid TFE (Kp = 3)	4140	56580	2274	17376	4656	0.388	64.7	23%
Hybrid TFE (Kp = 4)	4140	56580	2510	16976	4584	0.382	65.2	22%
Traditional TFE	5796	59076	1170	18000	8736	0.52	83.7	
Hybrid TFE (Kp = 2)	5796	59076	2064	18228	6720	0.4	63.6	24%
Hybrid TFE (Kp = 3)	5796	59076	2274	18009.6	6518.4	0.388	62.4	25%
Hybrid TFE (Kp = 4)	5796	59076	2510	17638.4	6417.6	0.382	62.8	25%

The Table 2 shows that K_R has a little effect on the specific fuel consumption. Therefore, K_R should be no more than 2 because of maximizing of the useful load.

4 Estimation of flight range for fixed useful load and takeoff mass

Consider the flight to the maximum possible range of 4 variants of aircraft with a fixed useful load of 15 t and fixed take-off mass of 54 t.

As the 1st variant the aircraft with TFE of traditional scheme on kerosene is chosen. The 2nd 3rd and 4th variants are modernized variant 1 by installing the new engine and the transition to a new fuel. The 2nd variant is TFE+SOFC on aviation kerosene, the 3rd is TFE+SOFC on liquid natural-gas (LNG) and the 4th – is TFE+SOFC on liquid hydrogen (LH).

In this section the flight profile includes takeoff, climb up to 11 kilometers and horizontal flight with the number of M = 0.78. After reduce the mass of fuel to a value of 10% from the initial fuel load (aeronautical stock), descent and landing is carried. As a result, the flight range is defined.

Basic summary masses of aircraft components as well as the specific parameters for researched engines are presented in Table 2.

The transition from the initial variant 1 (TFE on kerosene) to variant 2 (TFE + SOFC on kerosene) causes the growth of mass of the engine on 1788 kg. Accordingly, the fuel mass is decreased from 11080 kg to 9292 kg. By using LNG and LH the mass of the engine is also higher than the mass of the engine of the 1st variant. In order not to exceed the maximum take-off mass 54t, the fuel mass of 3rd and 4th variants has to be 9290 kg and 9740 kg respectively. This mass includes the mass of cryogenic fuel as well as a mass of cryogenic fuel tank (CFT). The Length of CFT in the 3rd and 4th variants is assumed to be equal to 28 m, but the diameter is found from the condition of maximizing the cryogenic fuel mass. The mass of 1 square meter of insulation for LNG is 20 kg and for LH 30 kg [7] . The aerodynamic qualities of the aircraft due to the cryogenic fuel tank is deteriorated on 3% for variant 3 and on 5% for variant 4 [7].

Table 2

Variant	1	2	3	4
Fuel	kerosene	kerosene	LNG	liquid H_2
Engine mass, kg	1170,0	2064,0	2065,0	1840,0
Cryogenic fuel tank mass, kg	–	–	1678,0	4963,0
Fuel mass, kg	11080,0	9292,0	7612,0	4777,0
Increase to the drag coefficient	0	0	+3%	+5%
Length of Tank, m	–	–	28,0	28,0
Diameter of Tank, m	–	–	0,92	1,77
Aeronautical stock, kg (10%)	1108,0	929,2	762,7	477,7
Useful Load, kg	15000	15000	15000	15000
Specific fuel consumption, kg/(kgf×hour)	0,53	0,4	0,33	0,132
Flight Range, km	4770	5090	5045	7705
Fuel efficiency, g/(t×km)	138	109	90	37
Emission of CO_2, kg	31384,0	26318,0	18815,0	0,0

Through the better efficiency the fuel consumption of 2nd, 3rd and 4th variants is significantly less than that of version 1. It causes the increase of the fuel efficiency. The fewer carbon content in LNG [C]=0,75 (variant 3) let to decrease emission of CO_2.

In this section the values of fuel efficiency are higher than that in the previous section. It is due to the taking into account the fuel consumption on takeoff, climb and landing.

5 Conclusion

TFE+SOFC on aviation kerosene let to increase the flight range on 6.7%, the fuel efficiency on 21% and to decrease emission of CO_2 on 16%. TFE+SOFC on LNG let to increase the flight range on 5.7% and the fuel efficiency on 34.7% and to decrease emission of CO_2 on 40%. TFE+SOFC on liquid hydrogen let to increase the flight range on 61.5%, the fuel efficiency on 73.2% and to eliminate emission of CO_2.

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