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FUNDAMENTALS OF THE THEORY OF AVIATION "ELECTROCHEMICAL" GAS TURBINE ENGINES WITH SOLID OXIDE FUEL CELLS

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Abstract

The systematic account fundamentals of the theory of hybrid gas turbine engines where fuel cell battery is used as source of energy in one line with traditional combustion chamber is represented at the report. The cause of using solid oxide fuel cells (SOFC) operates on synthesis gas, produced from liquid fuel is discussed. The direct current electric motor is represented as electric load for fuel cell battery.

Nomenclature

α – *air excess factor in the fuel cell battery*
k_{FU} – *fuel utilization in the fuel cell battery*
$\dot{m}_{fB}$ – *fuel mass flow rate in the fuel cell battery*
$\dot{m}_{aB}$ – *air mass flow rate in the fuel cell battery*
$\dot{m}_{K1}$ – *air mass flow rate after compressor I contour*
$\dot{m}_{K2}$ – *air mass flow rate after compressor II contour*
T_{K1} – *air temperature after compressor I contour*
T_{op} – *operation temperature of the fuel cell battery*
T_{T1} – *gas temperature in front of the turbine I contour*
$L_{AD\,K1}$ – *adiabatic work of the compressor I contour per unit mass*
$L_{AD\,K2}$ – *adiabatic work of the compressor II contour per unit mass*
$L_{AD\,T1}$ – *adiabatic work of the high pressure turbine per unit mass*
$L_{AD\,T2}$ – *adiabatic work of the low pressure turbine per unit mass*
ΔH – *enthalpy difference*
H_u^0 – *calorific value of the fuel*
δH_u – *undimensional losses of the fuel calorific value after its transformation into synthesis gas*
η – *efficiency*
η_B – *fuel cell battery efficiency*
η_{EF} – *turbofan engine efficiency*

1 Introduction

The new type of aviation engines, where the fuel cell battery is used for generation jointly combustion chamber is discussed at present technical literature [1-4]. The design and development of such engines is provided in Foresight of Development Aviation Science and Technologies (Russia) [5] until 2030. But main parameters estimation of hybrid engines and possible advantages of their using, has serious problems because questions of theory hybrid engines is not developed in proper degree. So the various assumptions are used instead firm knowledge.

In the report the selection of main parameters and statements for calculation operating process is performed for the systematic account fundamentals of the theory of hybrid gas turbine engines with fuel cell battery.

2 The Scheme of Engine

The using of fuel cell battery with gas turbine engine makes it possible to develop a new types of aeroengines. Let us discussed the possible scheme of turbofan engine (TFE) with solid oxide fuel cells (SOFC).

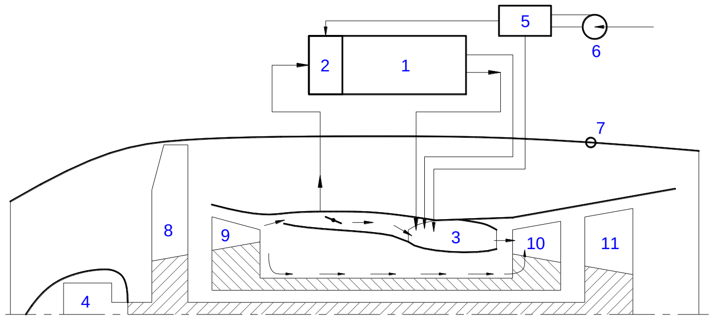

Fig. 1. The scheme of hybrid turbofan engine with solid oxide fuel cells

1 – SOFC battery; 2 – Reformer; 3 – Combustion chamber; 4 – Electric motor; 5 – Fuel regulator; 6 – Fuel pump; 7 – Low pressure contour nozzle; 8 – Fan; 9 – High pressure compressor; 10 – High pressure turbine; 11 – Low pressure turbine.

In contrast to well-known TFE, the new engine have the SOFC battery (1) and the direct current electric motor (4) in addition to traditional combustion chamber (3). The high pressure compressor feeds an atmospheric air through the channels in fuel reformer (2) and then in fuel cell battery (1). The fuel in special reformer is transformed into the synthesis gas for SOFC feeding. Because additional water using is not good from economical point of view for process of synthesis gas generation, then the process of preferential oxidation [6] is applied in this situation. Preferential oxidation process use atmospheric air and initial fuel for synthesis gas generation. Because some path of fuel energy will be eliminated during these process, the air from compressor (9) is used as cooler for reformer construction (2). The SOFC battery use synthesis gas from reformer as fuel and atmospheric air as oxidizer. The electric power produced by fuel cell battery is consumed by an electric motor (4), which with low pressure turbine (11) is actuating the fan (8) in low pressure contour.

The cathode and anode gases produced by fuel cell battery are burned up in the combustion chamber and come to the gas turbines which driving the compressor (9) and the fan (8). After turbines the overpressured gases get out to the nozzle for creating an additional trust.

3 The Base Parameters

The number of sources use an approach for fuel cell parameter calculation established on using of Nernst equation for determination a value of Electromotive force – E (EMF) of fuel cell and equation of potential difference as function of current density – j_C in fuel cell [6-9]. But it approximately calculations only. More correct calculation must takes into account a changing of gas in enthalpy and entropy into anode and cathode chambers, concentrations of active and passive components intake and outlet of these chambers and values of fuel and oxygen utilization.

It is shown, if the fuel utilization in fuel cell under various current densities is constant, then EMF and thermal efficiency – η_T of fuel cell are constant too [10].

A simple approach for calculation fuel cell energy characteristics has been proposed in [11].

The maximal power density from 1 cm^2 of fuel cell ($P_{SP\,MAX}$) has been proposed as parameter for defined the power perfection of fuel cell.

It is known, that the maximal power density in fuel cell has been obtained when ratio of external load and internal electric resistance of fuel cell is equal 1.

We can obtain, that efficiency of electric circuit is function of ratio of external and internal electric resistances in an electric circuit – K_R by using Kirchhoff rule:

$$\eta_E = \frac{K_R}{K_R + 1}. \quad (1)$$

It is possible to see that the power produced from 1 cm^2 of fuel cell active surface at its work on external electric load is connected with K_R value as:

$$P_{SP}^{0} = P_{SP\,MAX}^{0} \cdot \frac{4 \cdot K_R}{\left(K_R + 1\right)^2}\,. \tag{2}$$

At this relation parameter $P_{SP\,MAX}^{0}$ has been taken under normal pressure of the fuel cell reagents. If pressure of reagents increase – then values P_{SP} and $P_{SP\,MAX}$ are increased too [12]:

$$P_{SP\,MAX} = P_{SP\,MAX}^{0} \cdot \left(\frac{p}{p_0}\right)^{n}, \tag{3}$$

$$P_{SP} = P_{SP\,MAX} \cdot \frac{4 \cdot K_R}{\left(K_R + 1\right)^2}\,. \tag{4}$$

The value of specific power density – power per one mass unit of fuel cell battery construction, when fuel cell battery operates under condition $K_R = 1$:

$$P_{SP\,D} = P_{SP\,MAX} \cdot S_{a1} \tag{5}$$

may be proposed as parameter for estimation of energy – mass perfection of fuel cell battery.

In this correlation S_{a1} – is active square of fuel cells per one mass unit of fuel cell battery construction.

The total electric power generated by the fuel cell is:

$$N_{EL} = P_{SP} \cdot S_{a\Sigma} \tag{6}$$

where $S_{a\Sigma}$ is total active square of fuel cells in the fuel cell active zone.

4 The Specific Parameters Calculation

A hybrid TFE with SOFC battery and electric motor it is a complex system, more complex than traditional TFE. So the special methods for calculation and analysis of complex system operation shall be used for determination main parameters of hybrid TFE.

In particular the potential-stream method can be proposed for calculation of hybrid TFE parameters [13]. By these method all hybrid TFE is decomposed on a number of subsystems, which changing between other subsystems and environment by streams mass and energy.

The scheme of subsystem is represented on fig. 2.

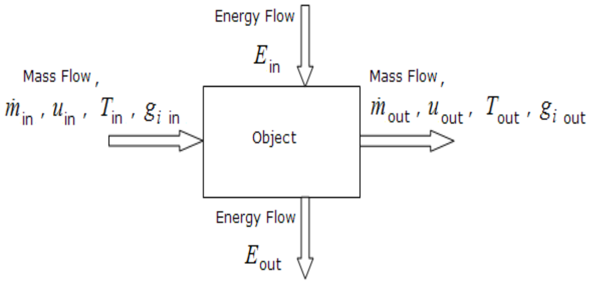

Fig. 2. The scheme of subsystem with changing streams mass and energy with neighbor objects

Let us assume that in the subsystem take place an energy elimination by chemical reactions and acceleration or deceleration mass flow on inlet or outlet. By using the total enthalpy concept the energy balance for subsystem, represented on fig. 7, can be written as:

$$\begin{gathered} \dot{m}_{in} \cdot \left[H_{t,\ in}\left(T_{in}\right) + \frac{u_{in}^2}{2}\right] + E_{in} = \\ = \dot{m}_{out} \cdot \left[H_{t,\ out}\left(T_{out}\right) + \frac{u_{out}^2}{2}\right] + E_{out} \end{gathered} \tag{7}$$

The total enthalpy for some substance [14] is defined as a sum a heat of formation for this substance at the temperature 298 K and difference between thermodynamic enthalpy at current temperature – T and thermodynamic enthalpy at the temperature 298 K:

$$H_t\left(T\right) = \Delta_f H\left(298\right) + H\left(T\right) - H\left(298\right).$$

When kinetic energy of flow is negligible in comparison with a total enthalpy the equation (*7*) can be written as:

$$\begin{gathered} \dot{m}_{in} \cdot H_{t,\ in}\left(T_{in}\right) + E_{in} = \\ = \dot{m}_{out} \cdot H_{t,\ out}\left(T_{out}\right) + E_{out} \end{gathered} \tag{8}$$

In case SOFC battery is a subsystem, where electrochemical reactions are performed under isothermic conditions:

$T_{op} = const$, the equation (*8*) can be written as:

$$E_{out} = -\dot{m} \cdot \Delta H_t \left(T_{op}\right). \qquad (9)$$

After transformations of this equation based on determination of total enthalpy we obtain a condition of heat balance in SOFC battery:

$$\alpha = \alpha_{MAX} \cdot [k_{FU} - \eta_B + \\ +\left(1 - k_{FU}\right) \cdot \delta H_u - g_{LOSS} - g_{add}] \qquad (10)$$

$$\alpha \ge 1$$

where:

$$\alpha_{MAX} = \frac{H_u^0}{L_0 \cdot \left[\Delta H_a\left(T_{op}\right) - \Delta H_a\left(T_{K1}\right)\right]}, \qquad (11)$$

$$\eta_B = \eta_T \cdot \eta_E \cdot \left(1 - \delta H_u\right) \cdot k_{FU}, \qquad (12)$$

$$g_{add} = \frac{H_g\left(T_{op}\right)}{H_u^0}, \qquad (13)$$

$H_g\left(T_{op}\right)$ – enthalpy of electrode gases which come out from battery;

g_{LOSS} – part of heat losses by thermal conductivity: $\Delta Q_{LOSS} = g_{LOSS} \cdot \dot{m}_f \cdot H_u^0$ in battery construction.

If we know α and η_B then we can calculate a SOFC battery specific power – N_{SP}. It is a power produced by SOFC battery to 1kg per second inspired air:

$$N_{SP} = \frac{H_u^0 \cdot \eta_B}{\alpha \cdot L_0}. \qquad (14)$$

The main distinction of hybrid TFE from gas turbine TFE – a possibility different variants of cruising mode operating. The most obvious variant – operating when all fuel and air come in fuel cell battery. The scheme of operating medium flows in these case is represented on fig. 3.

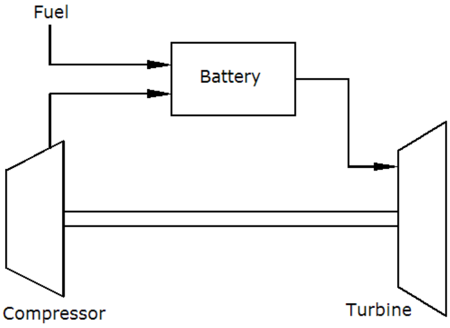

Fig. 3. The scheme of operating medium flow in hybrid TFE in case when all fuel and air are come to fuel cell battery

Another possibility – part of air flows to combustion chamber around fuel cell battery (fig. 4)

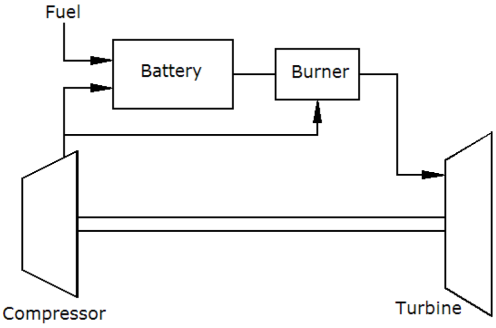

Fig. 4. The scheme of operating medium flow in hybrid TFE in case when part of air mass flow rate comes around fuel cell battery

In these case the temperature in front of high pressure gas turbine is decreased in comparison with variant on fig. 3. But mass flow rate on gas turbine can be increased at the same time. Operating under these scheme conditions a good possibility to decrease total power of turbofan engine.

The next possible scheme – some part of air and fuel come around fuel cell battery into combustion chamber (fig. 5).

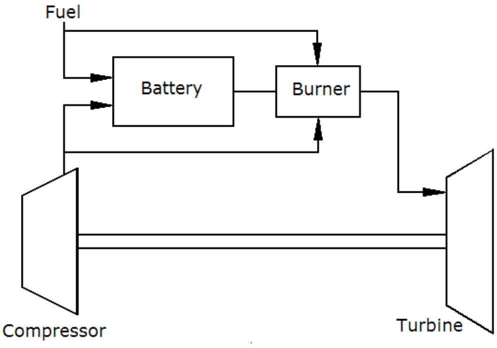

Fig. 5. The scheme of operating medium flow in hybrid TFE in case when part of air and fuel mass flow rates are come around fuel cell battery into combustion chamber

These variant makes possible significantly increasing power of gas turbine in comparison with fuel cell battery power. It may be necessary for takeoff flight vehicle from the ground.

Let us to discuss scheme on fig. 3, as more simple for analysis.

In these case the temperature in front of gas turbine is calculated by the gas enthalpy after combustion chamber:

$$\Delta H_g\left(T_{T1}\right)=\frac{H_u^0}{\left(1+\alpha\cdot L_0\right)}\cdot\left[1+\alpha\cdot L_0\cdot\frac{\Delta H_a\left(T_{K1}\right)}{H_u^0}-\eta_B-g_{LOSS}\right] \qquad (15)$$

The knowledge of T_{T1} allows to calculate a free turbine energy per unit airflow rate, which can be sented to contour II [15]:

$$N_{SP\,Free}=\left[L_{AD\,T2}\cdot\eta_{T2}-\frac{L_{AD\,K2}}{\eta_{K2}}\right]. \qquad (16)$$

The total value of free energy per unit airflow rate, which can be sented to contour II:

$$N_{SP\,II}=\left[L_{AD\,T2}\cdot\eta_{T2}+\frac{H_u^0\cdot\eta_B}{\alpha\cdot L_0}\right]-\frac{L_{AD\,K2}}{\eta_{K2}}. \qquad (17)$$

If we divide the (*17*) by the value $L_{AD\,K2}/\eta_{K2}$ then we obtain correlation for bypass ratio in hybrid TFE:

$$m=\left[L_{AD\,T2}\cdot\eta_{T2}+\frac{H_u^0\cdot\eta_B}{\alpha\cdot L_0}\right]\cdot\frac{\eta_{K2}}{L_{AD\,K2}}-1. \qquad (18)$$

We can determinate a stream parameters before nozzles I and II contours and calculate the specific thrust – thrust per unit airflow rate in I and II contours – $R_{SP\,I}$ and $R_{SP\,II}$ by gas dynamic formulas [15].

After that we can calculate an air mass flow rate in I contour for obtaining a demanded thrust:

$$\dot{m}_{a\,I}=\frac{R}{R_{SP\,I}+m\cdot R_{SP\,II}}. \qquad (19)$$

5 The Cruising Mode Efficiency

The basic gas generator of turbofan engine can be represented as a subsystem unit, which include of some subsystems of more lower level. In this case the equation (*8*) can be written for basic gas generator as:

$$\begin{aligned}&\dot{m}_{fB}\cdot H_u^0+\dot{m}_{K1}\cdot\Delta H_a\left(T_{K1}\right)=\\&=\dot{m}_g\cdot\Delta H_g\left(T_{T1}\right)+N_B+\Delta Q_{LOSS}\end{aligned} \qquad (20)$$

After transformations this equation we obtained a correlation for determination of hybrid TFE efficiency:

$$\eta_{EF}=\eta_B+\eta_{TC}\cdot\left(1-\eta_B-g_{LOSS}\right) \qquad (21)$$

where η_{TC} – efficiency of gas turbine unit of hybrid TFE:

$$\eta_{TC}=\frac{L_{AD\,T2}\cdot\eta_{T2}-\dfrac{L_{AD\,K2}}{\eta_{K2}}}{\Delta H_g\left(T_{T1}\right)-\Delta H_a\left(T_{K1}\right)}.$$

When heat losses in SOFC battery is negligible small: $g_{LOSS}\approx 0$ then

$$\eta_{EF}\approx\eta_B+\eta_{TC}\cdot\left(1-\eta_B\right). \qquad (22)$$

It is obvious, that the system efficiency with fuel cell battery is more higher than efficiency of gas turbine system.

Correlations (*21*, *22*) is suitable for case “all fuel and all air in fuel cell battery” (fig. 3).

In this case such important parameters as bypass ratio (m) and temperature in front of turbine (T_{T1}) are calculated values. But when they are given values, the operation TFE by scheme (fig. 5) is necessary.

If we discuss this case, then the equation (*8*) shall be written as:

$$\begin{aligned}&\left(\dot{m}_{fB}+\dot{m}_{f\,af}\right)\cdot H_u^0+\dot{m}_{K1}\cdot\Delta H_a\left(T_{K1}\right)=\\&=\dot{m}_g\cdot\Delta H_g\left(T_{T1}\right)+N_B+\Delta Q_{LOSS}\end{aligned} \qquad (23)$$

where $\dot{m}_{f\,af}$ – additional fuel mass flow rate in combustion chamber (3) (fig. 1).

The equation (*23*) have additional conditions of mass balance in TFE:

$$\dot{m}_g=\dot{m}_{f\Sigma}+\dot{m}_{K1}, \qquad (24)$$

$$\dot{m}_{f\Sigma} = \dot{m}_{fB} + \dot{m}_{f\,af}\,. \qquad (25)$$

The correlation for determination of hybrid TFE efficiency in this case:

$$\eta_{EF} = \eta_B \cdot \frac{\dot{m}_{f1}}{\dot{m}_{f\Sigma}} + \eta_{TC} \cdot \left(1 - \frac{\dot{m}_{f1}}{\dot{m}_{f\Sigma}} \cdot \eta_B - g_{LOSS} \cdot \frac{\dot{m}_{f1}}{\dot{m}_{f\Sigma}}\right) \qquad (26)$$

This correlation can be written as:

$$\eta_{EF} \approx \eta_{TC} + \eta_B \cdot \frac{\dot{m}_{f1}}{\dot{m}_{f\Sigma}} \cdot (1 - \eta_{TC}) \qquad (27)$$

when heat losses in battery are small.

Particularly when $\dot{m}_{f\,af} = 0$, from (*27*) we obtained correlation (*22*).

In case $\dot{m}_{f\,af} > 0$ correlation (*27*) can be written as:

$$\eta_{EF} \approx \eta_B + \eta_{TC} \cdot (1 - \eta_B) - \eta_B \cdot (1 - \eta_{TC}) \cdot \left(1 - \frac{\dot{m}_{f1}}{\dot{m}_{f\Sigma}}\right) \qquad (28)$$

Obviously the additional fuel injection in combustion chamber (3) (fig. 1) decreases efficiency of hybrid engine.

So when engine operates by scheme “all fuel and all air in fuel cell battery” (fig. 3) the maximal efficiency of hybrid engine and minimal thrust specific fuel consumption (TSFC) is obtained. But the bypass ratio will be maximal in this case.

From (*21*) follows that maximum η_B correlates with maximum η_{EF}. But in real engine the value of η_B have some restrictions. These restrictions are connected with mass of hybrid engine.

It is easy to see, that increased of the electric resistance ratio K_R causes an increase in the efficiency of electric circuit (*1*). It increase the efficiency of fuel cell battery (*12*) but decrease the power density in fuel cells (*4*). So the mass of fuel cell battery increases because the active surface of fuel cells should be increased to achieve demanded power. In this situation the quantity of heat power, that reaches to gas turbines is reduced and the mass of gas turbine unit decreases too. This picture quality illustrated on fig. 6.

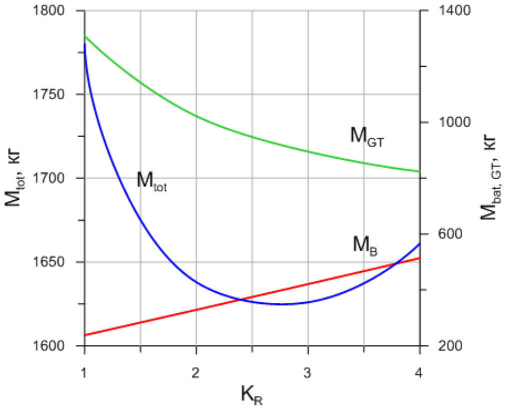

Fig. 6. Optimal value of ratio external load and internal fuel cell electric resistance for hybrid TFE

Increasing of K_R ratio increases the mass of fuel cell battery and decreases the mass of gas turbine unit. So the minimum mass of engine construction is obtained under optimal value of K_R.

Aviation engine, of any type has some influence on aircraft construction. This influence can be characterized by engine weight impact on aircraft. The engine weight impact on aircraft is a sum of engine construction mass and mass of consumed fuel during flight time.

It is proposed, when different engines have same weight impact their influence on aircraft construction is equal.

Let select a perspective mid-range aircraft for comparing hybrid and traditional TFE.

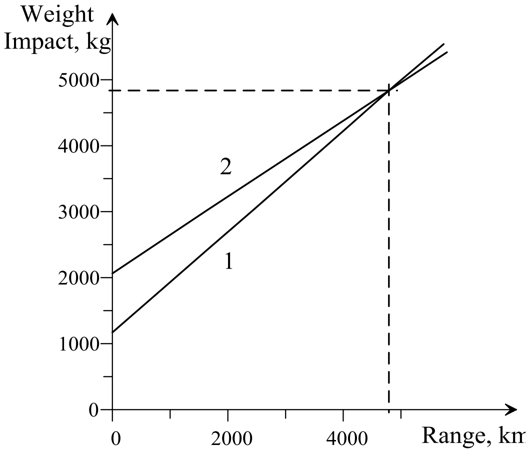

Fig. 7. The weight impact on aircraft as function of range for TFE (1) and hybrid TFE (2) for specific power density of fuel cell battery at 2,5 kW/kg and $K_R = 2$. Fuel – aviation kerosene.

An estimations of perspective engines mass and aircraft characteristics show [15] that the specific power density of fuel cell battery at 2,5 kW/kg is enough for creation equivalent hybrid TFE and traditional TFE for mid-range aircraft.

The proper value of efficiency electric circuit for hybrid TFE – $\eta_E \approx 66,6\%$.

It is common knowledge, that the heat efficiency of gas turbine engine is not depend from kind of fuel [16]. But such dependence takes place in case of the hybrid TFE with SOFC battery. The SOFC efficiency vs. used fuel is represented in table 1.

If the extremal heat efficiency of gas turbine unit may be estimated as 55% (fig. 8), then the efficiency of hybrid TFE with SOFC battery for various fuels can be represented at diagram (fig. 9). So the transition to hybrid TFE with SOFC battery instead of TFE can decrease TSFC on 20% in comparison with perspective TFE. In case of another kinds of fuel usage (liquid natural gas, liquid hydrogen) the gain of transition will be significantly large.

Table 1

The calorific value, losses after transforming of initial fuel in synthesis gas, the SOFC thermal efficiency and efficiency of SOFC battery for various fuels that can be used in hybrid TFE ($\eta_E = 0,666$; $k_{FU} = 0,85$)

Fuel	Kerosene	Liquid natural gas (LNG)	Hydrogen
H_u^0, kJ/kg	42900	50700	120000
δH_u	0,169	0,120	0,0
k_{FU}	0,85	0,85	0,85
η_T	0,720	0,743	0,790
η_B	33,5	37,0	46,5

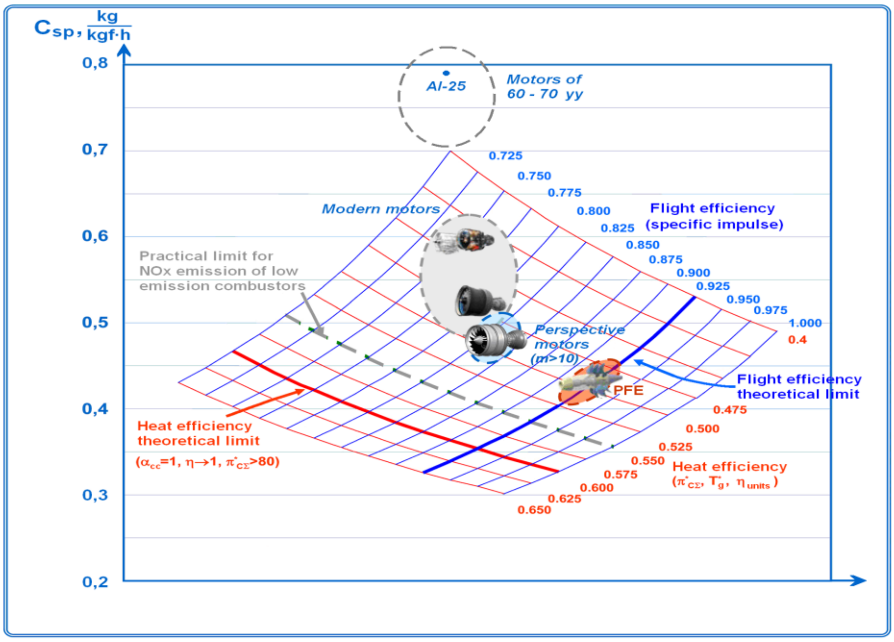

Fig. 8. The dependence of TSFC in gas turbine engines by the heat and flight efficiency for case at operation with kerosene as aviation fuel.

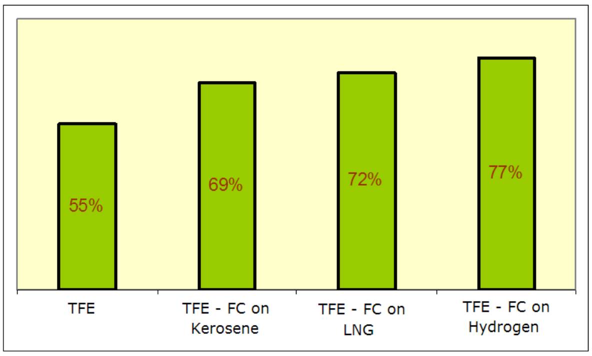

Fig. 9. The diagram of increasing hybrid TFE efficiency for various fuels

For the sample: a hydrogen usage as fuel for hybrid TFE decreases TSFC more than 30% in comparison with gas turbine variant.

The kerosene TSFC for perspective turbofan engine can be estimated value $0,45 \dfrac{kg}{kgf \cdot h}$ as it is shown on diagram fig. 8. So the possible TSFC of hybrid TFE with SOFC battery can be estimated $0,36 \dfrac{kg}{kgf \cdot h}$.

It is necessary to mark that this estimation is suitable for operating by scheme “all fuel and all air in fuel cell battery” (fig. 3) only.

6 The Distinctions of Takeoff Mode

The minimal values of TSFC in hybrid TFE with SOFC battery provides by big values of bypass ratio in this system. The bypass ratio of hybrid TFE are represented for various fuels in table 2. The calculations has been performed for the case of the hybrid TFE cruise mode that operating by scheme on fig. 3.

Table 2

The dependence bypass ratio (*m*) of hybrid TFE with SOFC battery for various fuels

Fuel	Bypass ratio (*m*)
Kerosene	23,0
Liquid natural gas (LNG)	25,5
Hydrogen	33,0

Big values of bypass ratio makes serious problems during engine operating in takeoff mode. The most massive elements of hybrid TFE is a fuel cell battery (1) and an electric motor (4) (fig. 1). To reduce the total mass of the system, it is necessary to run these elements at full power in all operating modes. So when we need a maximum power for airplane takeoff the TFE has to operate according to the scheme fig. 5, when the part of air and fuel supplied combustion chamber bypassing fuel cell battery. In this case the total value of free energy per unit airflow rate, which can be sented to contour II of engine, is:

$$N_{SP\,II} = \left[L_{AD\,T2} \cdot \eta_{T2} + \frac{H_u^0 \cdot \eta_B}{\alpha \cdot L_0} \cdot \frac{\dot{m}_{aB}}{\dot{m}_{K1}} \right] - \frac{L_{AD\,K2}}{\eta_{K2}} \cdot \qquad (29)$$

When the engine operates in cruise mode (fig. 3), the total value of free energy per unit airflow rate, which can be sented to contour II:

$$N_{SP\,II} = \left[L_{AD\,T2} \cdot \eta_{T2} + \frac{H_u^0 \cdot \eta_B}{\alpha \cdot L_0} \right] - \frac{L_{AD\,K2}}{\eta_{K2}} \cdot \qquad (30)$$

Obvious that the operating on takeoff mode creates additional load on the high pressure turbine (10) (fig. 1) because the difference between air mass flow rate in the battery and air mass flow rate in I contour decreases SOFC battery power per unit airflow rate in the I contour (*29*). So reduce of battery power should be compensated by increase of the adiabatic work of the turbine and accordingly the turbine temperature.

Let consider a hypothetic hybrid TFE with SOFC battery, that uses hydrogen as a fuel and provides cruise flight passenger aircraft at altitude 12000 m with velocity $0{,}8\,M$. The engine thrust during cruise flight – 1,2 *T* [15]. The hypothetic hybrid TFE created by scheme, represented on fig. 1, and operates during cruise flight under scheme “all fuel and all air in fuel cell battery” (fig. 3).

If the hypothetic hybrid TFE has outlet nozzles with constant cross section square, then it will have next main parameters of static operation (Table 3).

Table 3

Main parameters of hypothetic hybrid TFE with thrust 1,2 *T* during cruise flight under conditions static operating on sea level.

Ratio of external and internal electric resistances in an electric circuit Parameter	1	2	3
Thrust at sea level, T	10,5	10,0	9,8
Air mass flow rate in contour II, kg/s	361,0	367,0	367,0
Air mass flow rate in contour I, kg/s	36,0	24,0	19,0
Air mass flow rate in fuel cell battery, kg/s	8,9	6,3	5,2
Bypass ratio	10,0	15,0	19,3
Temperature in front of high pressure gas turbine, K	1850	1900	2100

As it is possible to see, the engine with scheme represented on fig. 1 should have very high parameters on gas turbine temperature during the static operation at sea level. So we have a contradiction between the engine operation under conditions of cruise flight and static operating on sea level.

To solve this problem, it is proposed a transfer to engine with distributed scheme, where a separated thrust fan is used for additional thrust generation with electric energy usage [17].

There is two thrust fans in distributed engine. One fan is driven by an electric motor (4) and located in a separate thrust contour. Another fan is placed in a low pressure contour and driven by gas turbine. The separation a thrust fans allows to reduce the free energy per unit airflow rate, which sented to contour II. It is easy to see that in this case:

$$N_{SP\,II} = L_{AD\,T2} \cdot \eta_{T2} - \frac{L_{AD\,K2}}{\eta_{K2}}. \tag{31}$$

$N_{SP\,II}$ has no significant difference between static operation at sea level and cruising operation at high altitude as engine on fig. 1. The temperature turbine estimation is shown that in this case the temperature in front of turbine is not risen 1500 K.

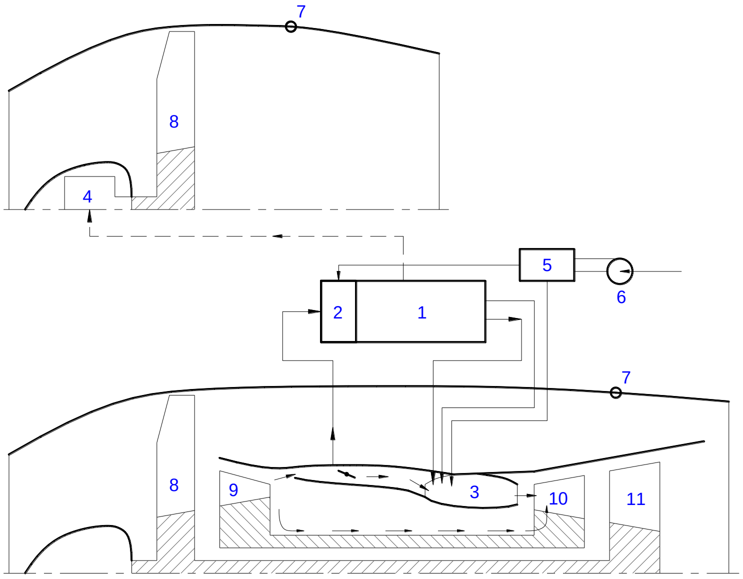

Fig. 10. The scheme of hybrid turbofan engine with solid oxide fuel cells and carry out thrust fan

1 – SOFC battery; 2 – Reformer; 3 – Combustion chamber; 4 – Electric motor; 5 – Fuel regulator; 6 – Fuel pump; 7 – Low pressure contour nozzle; 8 – Thrust fan; 9 – High pressure compressor; 10 –High pressure turbine; 11 – Low pressure turbine.

7 Conclusions

The fundamentals of the theory of the hybrid turbofan engine with solid oxide fuel cell battery is developed.

1. It is shown that there is the constant parameter group for the engine operating cycle:

- EMF fuel battery (E);
- the fuel battery thermal efficiency (η_T);
- the electric circuit efficiency (η_E);
- the fuel cell maximal power density (P^0_{MAX}).

The operating cycle specific parameters are:

- the air exceed factor (α);
- the fuel battery efficiency (η_B);
- the power produced by SOFC battery per unit inspired air (N_{SP});
- the bypass ratio (m);
- the free turbine energy per unit airflow rate, which can be sented to contour II ($N_{SP\,Free}$);
- specific thrust of both contours ($R_{SP\,I}$, $R_{SP\,II}$)

can be calculated by the constant parameter group.

All dimensioned data for the hybrid TFE can be determinated for the demanded thrust with the operating cycle specific parameters.

2. Correlation and determination the hybrid TFE parameters should be provided for the cruise mode operating conditions.
3. Some different modes of the hybrid TFE can be breathed under the same value cruise thrust.
4. The minimum values of TSFC can be reached if the hybrid TFE operates as “all fuel and all air in the fuel cell battery” scheme.
5. Creation of the hybrid TFE with SOFC battery and kerosene as a fuel make possible decreasing the TSFC on 20% in comparison with perspective gas turbine TFE.
6. In case of using another fuel, the gain of hybrid TFE with SOFC battery will be significantly large. Hydrogen as a fuel for the hybrid TFE provides decreasing of the specific fuel consumption more than 30% in comparison with the best gas turbine variant.
7. The specific power density of the fuel cell battery about 2,5 kW/kg is enough for creation of the hybrid TFE for the advanced mid-range passenger aircrafts.
8. Transfer to creation of the distributed hybrid TFE with SOFC battery makes possible to eliminate problems with high turbine temperature during aircraft takeoff from earth surface.

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