29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

RESEARCH OF EFFICIENCY OF THE MID-FLIGHT POWER PLANT BASED ON THE HYBRID ENGINES FOR ADVANCED AIRLINERS

Pavel Ryabov
Central Institute of Aviation Motors (CIAM), Moscow, Russia

Keywords: *Hybrid engine, fuel cell, gas fuel, airliner, efficiency*

Abstract

Purpose of conducted investigations is assessment of performance improvement of hybrid gas-turbine engine (HGTE) based on solid oxide fuel cell (SOFC) using cheaper and environmental alternative fuels (AF) such as liquid methane and propane-butane mixture (propane-butane).

Also purpose of the work is assessment of efficiency of mid-flight power plant (PP) based on HGTE for advanced short-medium hall aircrafts (SMHA) of 2025 (with level of parameters corresponding to technologies of 2025-2030 time period).

1 Introduction

The paper is focused on the consideration of 2 HGTE architectures with fan electromotor (EM) supplying by power unit (PU) or electrochemical generator (ECG) based on SOFC. ECG is device using oxidant and fuel results electric energy and fuel oxidation products. Possibility of use of any hydrocarbon fuels is a features of ECG based on the SOFC.

Purpose of conducted investigations is assessment of performance improvement of HGTE based on SOFC using cheaper and environmental AF such as liquid methane and propane-butane, which are produced commercially and used extensively in automobile transport. Also purpose of the work is assessment of efficiency of PP based on HGTE for advanced SMHA entering into service in 2025.

Studies are based on the predictions of aviation development of domestic (TsAGI, CIAM [1, 2, 3] and foreign (NASA [4, 5], Boeing, etc.) experts relevant to 2025.

2 Statement of problem

Selection of gas-turbine part of engine architecture has decisive importance at the preliminary design of HGTE. HGTE architecture defines not only its fuel and mass-dimensional performances but also practical feasibility and connected with it different risks.

Classical 2-spool turbofan with the booster, high bypass ratio BPR=13-15 and component efficiencies and parameters predicted for 2025 time period is considered as reference engine for HGTE architectures studies (Fig. 1, a).

2.1 Object of research

2 base HGTE architectures without boosters and based on turbofan with high engine cycle parameters are considered in the:

- Architecture HGTE-1 – usage of additional supply of fan spool by mechanical power from EM. Electrical energy to supply EM is generated by external source, i.e. PU based on SOFC (see Fig. 1, b).
- Architecture HGTE-2 – usage of ECG based on SOFC, operating in parallel with main combustor. Like HGTE-1 electricity generated by ECG supplies EM, located on the fan shaft. Remaining heat generated by operation of ECG supply fan turbine (see Fig. 1, c).

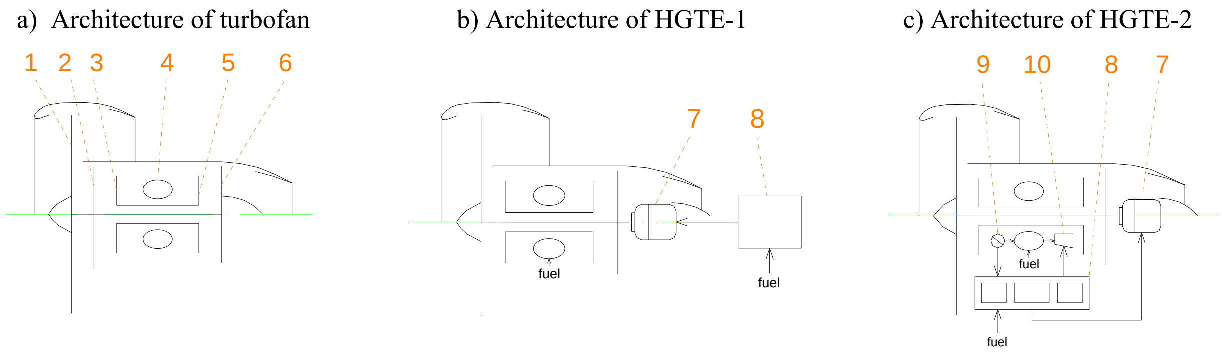


Fig. 1. Architecture of turbofan and HGTE

1 – fan, 2 – boosters, 3 – compressor, 4 – combustor, 5 – compressor turbine, 6 – fan turbine, 7 – EM, 8 – PU for HGTE-1 or ECG for HGTE-2; 9 – valve of regulating of air distribution between the ECG and combustor, 10 – mixer of gases from the ECG and combustor

2.2 PU type selection

PU type selection of HGTE-1 for a power supply of EM is conducted by several reasons. Unlike SOFC, use of Polymer Electrolyte Membrane Fuel Cell (PEM FC) assumes work only on high purity hydrogen. PU based on SOFC will also have higher efficiency depending on applied fuel type. For example, according to a forecast of CIAM experts by 2025, efficiency PU based on PEM FC using hydrogen can reach by 50-60%. PU based on SOFC using kerosene, propane-butane, methane [1] and hydrogen may reach by 50%, 59%, 62% and 70% accordingly.

Application of storage battery (SB) as PU is strongly limited due to time of its effective use on aircraft (see Fig. 2).

In case of identical specific performance of PU (based on SOFC) and SB, SB is effective if

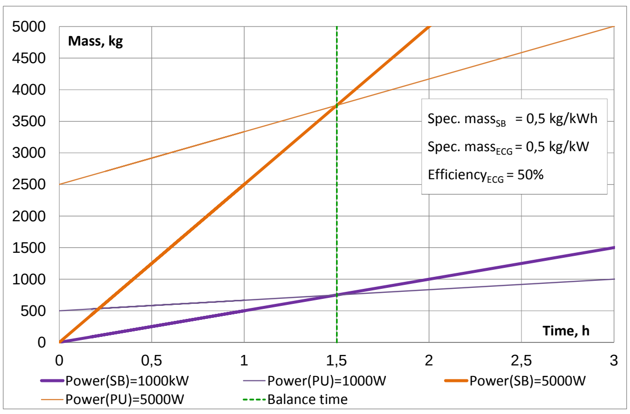


Fig. 2. Comparison of SB and PU+kerosene mass from operating time

time of its work is short (see Fig. 2). SB specific energy predicted for 2025 is estimated by around 1.0-1.5 kg/(kW·h) [4], unlike as given on Fig. 2. It means that time of effective use of SB will be essentially shorter.

It should be noted that time of effective use of these PU types does not depend on level of consumed electric power (see Fig. 2).

2.3 Principle of ECG operation

ECG is the common and key component of considered HGTE architectures. The oxidizer and fuel are ECG input components, and electric power and reaction products are ECG output components.

ECG consists of following elements (see Fig. 3): reactor of conversion (reformer), SOFC and reburning chamber. Conversion of kerosene to synthesis gas (a mixture of H_2 and CO) is occurred in the reformer. H_2 and CO oxidation with direct transformation of chemical energy to the electric is conducted in SOFC. The remains

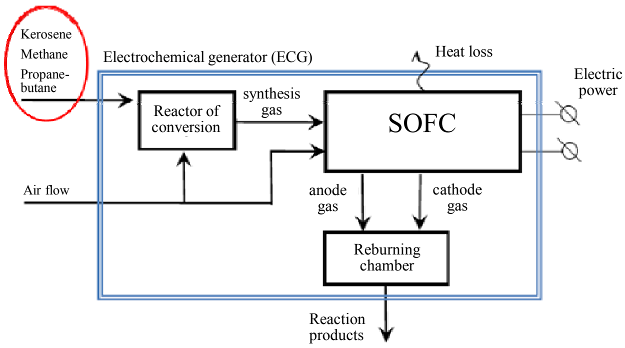


Fig. 3. Scheme of ECG

of reagents are reburned in the ECG reburning chamber.

Key feature of ECG based on SOFC is capability of using of practically any hydrocarbon fuel. Nowadays kerosene, methane, etc. are considered as the most promising fuel types.

3 Generation of HGTE design parameters

Generation of HGTE design parameters was carried out for SMHA under cruise conditions (initial altitude of cruise flight $H_{in\ cr}$=11 km, the Mach number M_{cr}=0.78) taking into account a supply of additional electric power to drive fan shaft and using of ECG mathematical model. Requirements to cruise and takeoff thrusts and different restrictions are taking into account during calculation [6].

Evaluable investigation of influences of engine cycle parameters (turbine entry temperature TET, overall pressure ratio OPR, bypass ratio BPR) and relative electrical power input $\delta N_e=N_e/(N_e+N_{LPT})$ on fuel efficiency, thrust and mass-dimensional parameters of HGTE are carried out in the work (here N_e is EM power, N_{LPT} is power of LPT for fan driving). The value δN_e for HGTE-2 was defined by a ratio of air flows W_{ECG}/W_c (where W_{ECG} and W_c are inlet air flows of ECG and compressor accordingly).

Spaces of cruise design parameters of HGTE using methane and propane-butane as fuel are very like similar spaces of HGTE using kerosene [1].

Several HGTE-1 and HGTE-2 variants with different combination of design parameters are selected from each of spaces (see Table 1).

Table 1. The HGTE design parameters on kerosene

	HGTE-1-K					HGTE-2-K				
№	N_e, %	BPR	CPR	TET, K		W_{ECG}/W_c	N_e, %	BPR	CPR	TET, K
1	20	20	20	1600		90	54	20	17	1300
2	75	20	20	1200		70	43	17	20	1300
3	75	20	20	1400		70	44	20	19	1350
4	75	20	20	1600		70	42	13	19	1300
5	50	10	20	1300		70	45	10	13	1300
6	50	20	15	1400		50	30	17	20	1400
7	50	20	20	1300		90	64	20	20	1300
8	50	20	20	1450						
9	50	20	20	1600						

Calculation of altitude-speed and throttling performances in given flight conditions and wide range of throttle ratings is performed for these engine variants to further evaluation of SMHA mission performances.

The best variants of HGTE-1 and HGTE-2 using kerosene (K), methane (M) and propane-butane (PB) were selected from extensive number of considered variants: variant №7 (HGTE-1(7)-K, HGTE-1(7)-M and HGTE-1(7)-PB); variant №2 (HGTE-2(2)-K, HGTE-2(2)-M and HGTE-2(2)-PB). These variants are indicated by red in Table 1.

4 Determination of the SMHA design parameters

The efficiency assessment of PP with HGTE was carried out on mission performance of advanced twin-engine to the SMHA with passenger capacity N=180 and range of R=5000 km. The sizes of the engines with parameters predicted by 2025 were defined.

Optimal variants of HE were selected using mathematical model of aircraft and engine matching under mission, takeoff/landing and emission criteria. [1].

Following level improvement of parameters of SMHA components and PP with HGTE based on the SOFC of predicted for 2025 time period are assumed in the calculations: cruise aerodynamic efficiency $(L/D)_{cr}$=22, specific mass of gas turbine part (GTP) of HGTE γ_{GTP}=0.167 kg/kW, and all PU γ_{PU}=0.5 kg/kW, PU efficiency $\eta_{PU\ K}$=0.5, $\eta_{PU\ M}$=0.62, $\eta_{PU\ PB}$=0.59, specific mass of EM γ_{EM}=0.1 kg/kW [1].

Additional power offtakes from PP for aircraft needs during all flight, as well as physical and gas-dynamic restrictions, relating to operation of HGTE as a part of SMHA PP took into account at carrion out of mission assessment of SMHA with selected variants of HGTE.

Construction of fuselage of SMHA like MS-21-300 is given as a base. Twin mount cylindrical balloons installed in front cargo bay under the floor and one spherical balloon isolated by additional pressurized bulkhead and installed behind the passenger cabin are reasonable installation of fuel tanks (FT) for liquid (cryogenic) gas fuel arrangement (see Fig. 4).

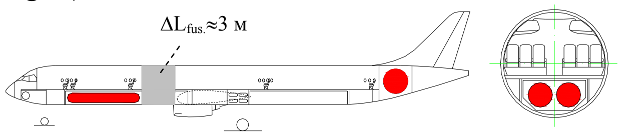


Fig. 4. Arrangement of cryogenic fuel tanks

5 Assessment of HGTE efficiency

Main results of assessment of fuel efficiency of SMHA with best selected HGTE variants using different fuels are presented on the Table 2. The abbreviations and indices of Table 2 are: “T” – trust, “W” – mass, “V” – flight speed, “S_W” – wing area, “L/D” – lift to drag ratio, “N” – passenger capacity, “SFC” – specific fuel consumption, “$W_{fuel}/(N·R)$” – aircraft fuel efficiency, “R” – flight range, “BFL“ – balance field length, and “T/O” – takeoff, “cr” – cruise, “ANF” – aero navigation fuel.

As it is seen using of propane-butane decreases fuel efficiency of HGTE-1 relating to turbofan using kerosene. However, taking into account a different fuel price, advantage of propane-butane can be more than 40%.Using of methane as a fuel provides best fuel efficiency of SMHA with HGTE.

Achievement of advanced ICAO and NASA environmental goals for 2025-2030 time period in term of life cycle CO_2 emission and noise is expected for SMHA with HGTE using gas fuel [1, 4, 5].

6 Analysis of results

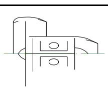
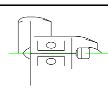
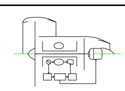
It is obvious that the selection of the engine architecture in a combination with used fuel will be defined by set of requirements to developed SMHA, first of all by enviromental, and also technology readiness level (TRL). Existing difference in the price of gas fuel relating to kerosene (-75% for methane, -50% for propane-butane, typical for Russia), fuel price raise dynamics create good background to serious consideration of advanced SMHA concept with HGTE using just gas fuel.

Obtained results allow focus on improvement of integral economic efficiency of SMHA with HGTE in comparison with conventional turbofan, at same time, high level of technical risk makes the conclusion as multiple-value and needs further investigations taking into account real progress in growth of the critical technologies for HGTE and cost, operating, political and other factors.

7 Conclusion

1. The approach to definition of design

Table 2. Main mission performance of SMHA 2025 with turbofan and HGTE ($H_{in\ cr}$=11 km, M_{cr}=0.78)

Architecture of HGTE								
Parameters		**Reference turbofan**	**HGTE-1(7)-K**	**HGTE-1(7)-M**	**HGTE-1(7)-PB**	**HGTE-2(2)-K**	**HGTE-2(2)-M**	**HGTE-2(2)-PB**
$(T/W)_{T/O}$	kgf/kg	0,283	0,283	0,283	0,283	0,283	0,283	0,283
$W_{T/O}/S_W$	kg/m²	500	500	500	500	500	500	500
$\boldsymbol{W_{T/O}}$	**kg**	**53240**	**58085**	**59775**	**61880**	**54400**	**574340**	**58690**
$T_{T/O}$	kgf	7535	8220	8440	8730	7695	8110	8285
$(L/D)_{cr}$	-	22	22	21,84	21,84	22	21,85	21,85
V_{cr}	km/h	828,7	828,7	828,7	828,7	828,7	828,7	828,7
$\boldsymbol{T_{cr}}$	**kgf**	**1175**	**1280**	**1325**	**1370**	**1200**	**1270**	**1300**
$\boldsymbol{SFC_{EFcr}}$	**[kg/(kgf×h)]**	**0,508**	**0,515**	**0,408**	**0,454**	**0,425**	**0,368**	**0,399**
R_{ANF}	km	700	700	700	700	700	700	700
R	km	5000	5000	5000	5000	5000	5000	5000
$\boldsymbol{W_{fuel}/(N \cdot R)}$	**g/(pax·km)**	**8,12**	**8,98**	**7,62**	**8,72**	**7,03**	**6,65**	**7,33**
%		-	10,5	-6,2	7,3	-13,4	-18,1	-9,8
BFL	m	2000	1990	1975	1985	1925	1945	1950

parameters PP based on hybrid engines for advanced airliners using different fuels is developed.

2. The applied approach allows selecting rational HGTE-1 and HGTE-2 architectures, estimating their efficiency and creating the list of critical technologies of elements HGTE.

3. Considered level of HGTE parameters potentially can provide SMHA advantage relative to turbofan by fuel efficiency and, respectively, CO_2 emission.

4. Using of AF, particularly methane, will allow improving efficiency of SMHA with HGTE based on SOFC in comparison with using of kerosene. It will allow coming nearer to target indicators of ICAO and NASA of 2025-2030.

References

[1] Ryabov P, Kalenskiy S, Khaletskiy Y, Mirzoyan A. Efficiency assessment of HPS for advanced airliners using different fuels. *Aircraft Engineering and Aerospace Technology (AEAT) Journal*, Vol. 86, Issue 5, 2014 (be in print).

[2] Selivanov O.D., Lukovnikov A.V., Ryabov P.A., Maximov A.A. Studies of propulsion system concepts for advanced subsonic airliners. *Proc ICAS 2012*, Brisbane, Australia, CD-ROM ISBN 978-0-9565333-1-9, 2012.

[3] Ryabov P.A., Lukovnikov A.V., Selivanov O.D., Maximov A.A., Mirzoyan A.A. Development of hybrid engines concepts for advanced airliners. *Proc IAC'12*, Moscow, Russia, Vol. 1, 2012.

[4] Marty Bradley, Chris Droney, Dave Paisley, Bryce Roth, Srini Gowda, Michelle Kirby. *Subsonic Ultra Green Aircraft Research.* Final Review, Boeing, April 20, 2010.

[5] Marty Bradley and Christopher K. Droney. *Subsonic Ultra Green Aircraft Research. Phase II: N+4 Advanced Concept Development.* NASA/CR-2012-217556, May, 2012.

[6] Lukovnikov A., Selivanov O., Ryabov P., Ezrokhi Yu., Kalensky S. The hybrid propulsion systems for the advanced aircraft. *Proc ICAS 2014,* St. Petersburg, Russia, September 7-12, 2014 (be in print).

Acknowledgments

The author would like to acknowledge Dr. A. Baykov, Mr. I. Averkov and Dr. S. Kalensky – the staffs of CIAM for participation in collaboration and the provided characteristics of ECG and PU based on SOFC. The data provided by our colleagues were a base of our assessment of integral characteristics of SMHA and PP with HGTE for 2025.

Contact Author Email Address

ryabovp@ciam.ru

Copyright Statement