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ОПТИМИЗИРАНЕ НА ЦИКЪЛА НА ТУРБОВАЛЕН САМОЛЕТЕН ДВИГАТЕЛ, РАБОТЕЩ НА ТЕЧЕН ВОДОРОД

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OPTIMIZATION OF THE CYCLE OF A TURBOSHAFT AIRCRAFT ENGINE WORKING ON LIQUID HYDROGEN

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Abstract: Nowadays the hydrogen is regarded as one of the possible solutions of the problem of making the civilian aviation carbon neutral. The most efficient form of storing hydrogen onboard, so far is the liquid hydrogen (LH₂). Even this type of storage has significant drawbacks in comparison with the hydrocarbon fuels, mainly connected with the low energy density of LH₂. One of the ways of minimizing this drawbacks is by using all the possibilities to optimize the power plant of the aircraft for using LH₂. Possible hydrogen power plants include fuel cells and gas turbines where gas turbines are regarded as a solution for medium and large aircraft. In this article some optimizations of the LH₂ fueled gas turbine cycle are proposed. In this number the use of the LH₂ fuel as a inter-coolant for the compressor air and simplification of the combustor chamber, when hotted hydrogen is used. These optimizations are evaluated by simulating them in the GasTurb gas turbine performance software. The results show possible improvement in engine cycle efficiency of up to 3-4% and possible reduction of the engine weight and size by 2-3%.

Keywords: hydrogen fuel, gas turbine, gas turbine cycle simulation

1. INTRODUCTION

The idea of using cryogenic/ liquid hydrogen (LH₂) for gas turbine in commercial aircraft is not new. Pioneering research in this area was conducted in Soviet Union in 1980-x with the Tu-155 experimental aircraft [8]. The aircraft was a modified Tu-154, equipped with cryogenic fuel tank in the rear of the fuselage and one of the engines redesigned to use

hydrogen or methane. Nowadays this idea has a new life in the context of the carbon neutral air transport. Most remarkable is direction is the ZEROe program announced by Airbus. An important part of this effort is to predict the performance of the gas turbine engines that are optimized to use hydrogen. Good examples of analysis of the gas turbine cycle with hydrogen are [1, 2, 3, 4, 5, 7]. The first of these papers is from 2007 [3] and three of them are from 2021 [1, 5, 7] which is indicative for the rise of the interest towards the LH2 as an aviation gas turbine fuel. Generally the published research is for turbofan engines. At the same time the turbo propeller engines are of special interest because it is expected that in their power range they will compete with the proton exchange membrane fuel cell technology. For this reason the assessment is performed for a mathematical model of a typical contemporary turbo propeller engine – PW150A, which is used for 80 to 100 seat passenger twin turboprop airplanes (De Havilland Canada DHC-8 Q400).

As the main disadvantage of the LH2 is its low energy density, compared to the hydrocarbon fuels, it is important to minimize as much as practical the size/weight and the fuel consumption of the engines in order to counter this disadvantage. In this paper three factors that can bring improvement of the LH2 fueled gas turbine, compared to kerosene fueled gas turbine engine are assessed:

- Firstly it is the increase of the specific power of the turbine because the higher heat capacity of the H₂O – air exhaust gas compared to the H₂O, CO₂ – air.
- The second one is that better combustion efficiency and smaller pressure losses in the combustion chamber are achievable because of the better combustion properties of the hydrogen compared to kerosene.
- The last one is the possibility to use the LH2 as a coolant for the compressor air in order to improve the efficiency of the compression.

2. SIMULATION AND RESULTS

2.1 Calculation methodology and software..

The calculations are made with GasTurb11 gas turbine performance software. The software is based on the theory described in [6]. The properties of different fuels and combustion gas mixtures are calculated with the use of the NASA developed Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. Both kerosene and H₂ are covered. The calculations of the engine cycle are made for sea level maximum takeoff mode.

2.2 Baseline engine. The Pratt & Whitney Canada PW150 turbo propeller engine is a three shaft engine with a two stage power turbine, three stage axial low pressure compressor (LPC), driven by a single stage axial, intermediate pressure turbine, and a single stage high pressure compressor (HPC), driven by a single stage axial, high pressure turbine. The author assumes that this engine architecture is capable of easily accommodate an air to LH2 heat exchanger in the duct between the LPC and HPC, without significant rise in the pressure losses and the size of the engine.

Officially published data for the engine (in the EASA type certificate data sheet) is presented in table 1. As far as this data is not enough for the engine modeling, some estimates found in open sources are used – the compressor pressure ratio is assumed to be 18 and equivalent specific fuel consumption (ESFC) is 0.263 kg/kW.h. All other engine parameters in the model are arbitrary set in order to achieve the required power, jet thrust and ESFC.

Table 1. Baseline engine PW 150A characteristics.

Maximum Continuous Shaft Power, kW	3781
Jet Thrust at Maximum Continuous mode, N	3750
Dry Mass, kg	716.9
Propeller shaft speed, 1/min	1020
LP shaft speed, 1/min	27000
HP shaft speed, 1,min	31150

2.3 Assumptions and simplifications. To compare the LH2 engine with the baseline engine cycle the following assumptions are made:

- The efficiencies of the respective compressors and turbines of all of the engine configurations are as of the baseline engine.
- The turbine inlet temperature is as that of the baseline engine (1500K).
- The equity of the equivalent power of all of the configurations is reached through the change of the engine air flow.
- The different needs of the gas turbine blades for cooling in regard to the properties of the hot gases are not reflected in this study.
- It is assumed that the air-LH2 heat exchanger of the last explored configuration will not increase the pressure losses in the compressor inter-duct, as the large temperature difference will allow a low contact area heat exchanger.

In addition to the mentioned assumptions, for the engine configuration with LH2 intercooling of the compressor air the cooling capacity of the used fuel should be assessed. For this study the H₂ heat of vaporization $\Delta H_{vap} = 447$ kJ/kg is used. Also it is assumed that the hydrogen will continue to be heated in the heat exchanger to a temperature that is close to the temperature of the exhaust gases. The heat extracted by the hydrogen is calculated using equation 1.

$$(1) \quad Q_{H_2} = W_F \cdot (\Delta H_{vap} + c_{pH_2} \cdot \Delta T), kJ/s$$

, where W_F is the fuel flow in kg/s, $c_{pH_2} = 14.31$ kJ/kg.K is the heat capacity of hydrogen gas, and ΔT , K is the temperature rise of the vaporized hydrogen in the heat exchanger. The H₂ critical temperature is 33.2 K and the total air temperature at the LPC exit of the baseline engine is 436 K, so it is assumed $\Delta T=400$ K.

2.4 Figures of merit. The aim of this study is to measure the impact of the LH2 fuel on the mass of the engine and its fuel consumption. The weight of an engine can be estimated only when a great number of technological factors is accounted for. This is beyond the scope of the study and for this reason it was assumed that investigated engines have approximately the same specific mass, thus the engine dry mass will be proportional to the air flow of the respective engine. In this case for comparing the weight of the LH2 configurations with the baseline engine the relative difference of the air flow can be used:

$$(2) \quad \overline{\Delta W_a} = \frac{W_{aLH2} - W_{abase}}{W_{abase}} \cdot 100\%$$

, where the index 'LH2' is for the respective hydrogen fuel configuration of the engine and index 'base' is for the baseline engine.

The fuel consumption of the kerosene and LH2 engines cannot be directly compared. In this case the thermal efficiency is the only practical parameter:

$$(3) \quad \eta_{th} = \frac{P_{shaft} + F_{jet} / \beta}{W_F \cdot H_u}$$

, where P_{shaft} is the shaft power of the engine, the F_{jet} is the jet thrust, $\beta = 15$ N/kW is the typical static thrust to power conversion factor for equivalent power evaluation, and H_u is the lower heat of combustion. It is also interesting to know the relative difference of the thermal efficiencies of the investigated engines:

$$(4) \quad \overline{\Delta\eta_{th}} = \frac{\eta_{th LH2} - \eta_{th base}}{\eta_{th base}} \cdot 100\%$$

2.5 Results. The baseline engine and three configurations fuelled with hydrogen are calculated in GasTurb11. The hydrogen fueled configurations are as follow:

- In Configuration 1 there are no other changes except the hydrogen fuel.
- In Configuration 2 is assumed that the pressure ratio of the burner is increased from 0.93 for the baseline engine, to 0.96.
- In Configuration 3 a LH2 cooled intercooler in the compressor is added.

The results are shown in table 2. As expected the size and efficiency parameters gradually improve from Configuration 1 to Configuration 3.

Table 2. Baseline and LH2 engines comparison.

	Baseline engine	Configuration 1	Configuration 2	Configuration 3
W_a , kg/s	14	13	12,78	11.85
$\overline{\Delta W_a}$, %		-7.14	-8,71	-15,36
η_{th}	0.317	0.331	0.337	0.355
$\overline{\Delta\eta_{th}}$, %		4.55	6.36	12.13

3. CONCLUSIONS

The results of this survey show clearly that significant improvement of the characteristics of the turbo propeller engines could be expected if LH2 is used as fuel. This advantage, together with the hybrid and distributed propulsion technologies will compensate to some extent the complexity and low energy density of the LH2 storage system on board the aircraft. This study should be regarded only as preliminary step and the research should be continued in many directions including the engine, the LH2 storage and the optimal airplane configuration. Separate research efforts are needed to make a comparative evaluation of turbo propeller engines and various types of fuel cells as a propulsion systems for LH2 fuelled regional passenger airplanes.

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