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PRELIMINARY ANALYSIS OF THERMODYNAMIC CYCLE OF TURBOFAN ENGINE FUELLED BY HYDROGEN

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Abstract

Presented article is focus on analysis of the effect of hydrogen fuel on turbofan engine performance. Selected properties of hydrogen and possibility of introduction in civil aviation were discussed. Hydrogen implementation as aviation fuel offers obvious advantages such as low emission of combustion product, higher payload, lower fuel consumption, general availability but also poses great technical challenges. The most important aspect is to ensure engine operational safety at very high level. Hydrogen implementation would eliminate the aviation dependence of exhausting sources of fossil fuels especially of crude oil. The thermodynamic model of turbofan engine was implemented in MATLAB environment. Accepted assumptions have been discussed. Turbine cooling process has been included in the numerical model. Working fluid was modelled as semi-perfect gas. Analysis was carried out for take-off and design point conditions. Engine performances were compared for two kinds of applied fuels: liquid hydrogen and commonly used in turbine engines kerosene. Combustion heat of hydrogen is about three time higher than in comparison with conventional turbine engine fuel, what exert significant influence on engine performance. The results of engine thermodynamic cycle analysis indicate the increase in specific thrust and significant reduction of specific fuel consumption. The results are presented in tabular form and on the graphs. Obtained results have been discussed and the direction of further research was indicated.

Keywords*: liquid hydrogen, turbofan engine, turbine cooling, engine thermodynamic cycle, engine performance*

1. Introduction

Due to depletion of natural sources of fossil fuels and continuous energy demand, researches are conducted on possibility of using alternative fuels in aviation and other means of transport. Nowadays, the promising alternative fuel for aviation is hydrogen. Transition from kerosene to hydrogen fuel will be a long process but the historical events are a good example, that hydrogen implementation as aviation fuel is possible.

In 1956 took place first flight of bomber Martin B-57 Canberra aircraft, which one of two engines was adapted to burning both kerosene and hydrogen fuel. Liquid hydrogen was stored in the fuel tank located under left wing tip. Aircraft during the start and landing was supplied by conventional aviation fuel in both engines, whereas during the flight had possibility to burnt hydrogen into modified J-65 engine. The amount of stored liquid hydrogen allow for 21 minutes of engine work. Flight tests were a success and proved reliable and safety engine operation [2, 13].

By mid-August 1956, was designed new engine capable to burning liquid hydrogen as fuel, denote as ‘304’. High-pressure pump was used to pumped liquid hydrogen through heat exchanger, situated behind the turbine in the rear section of the engine. Heated hydrogen drove the turbine and turbine drove the fan by the reduction gear. Some amount of hydrogen discharged form turbine was burned in the air stream in the section behind the fan. This amount of burned fuel was under control to reduce exhaust gases temperature, which deliver the heat-to-heat exchanger. Remaining amount of hydrogen was burned in afterburner section at the rear of the engine, behind the heat exchanger. The main problems encountered during the implementation of this project were concerned on high-pressure pump and heat exchanger [14].

The other example is Russian Tupolev Aircraft Company, which in 1988 conducted researches on modified Tu-154 aircraft, powered by three engines. The first flight of prototype aircraft marked as Tu-155, took place on 15-th of April. One of three engines, centrally located, was able to run on hydrogen fuel while the other two was run on kerosene. Cryogenic cylindrical tanks for hydrogen were placed in the rear part of the fuselage, in front of power plant. Modified engine was also adapted for burning methane as fuel [2].

In 2000 year started European 'Cryoplane' project, which lasted for over two years [12]. Project was focused on the development and introduction of liquid hydrogen as an aviation fuel. Conducted analysis confirms that hydrogen is permissible fuel for future aviation. Estimation has been made that first implementation of hydrogen in aircraft transport will be possible by 15-20 years.

2. Hydrogen properties and possibility of application in civil aviation

Hydrogen is named 'clean' energy carrier, due to low emission of combustion gases. The main products release during combustion is water vapour (H_2O) and nitrogen dioxides (NO_x). There is a lack of exhaust components characteristic for hydrocarbon fuels, such as carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxides (SO_x), unburned hydrocarbons (UHC) and smoke [1]. All product released during hydrocarbon fuel combustion process contribute to climate changes. Emission of NO_x resulting from hydrogen combustion is much lower compared to conventional fossil fuel-based aviation fuel, while the emission of water vapour is about 2.5 time higher. Water vapour is a greenhouse gas like carbon dioxide and its residence time in atmosphere increase with the altitude. In contrast to carbon dioxide, lifetime of water vapour in atmosphere is relatively short and average several days up to one year, when residence time of carbon dioxide is about 100 years [1].

Selected properties of hydrogen and conventional aviation fuel are compared in the Tab. 1. Hydrogen has 2.8-time higher energy content per unit mass than kerosene, which means that a much larger amount of heat is supplied to the combustion chamber. This hydrogen property caused that it found practical application in rocket propulsion systems [10]. Hydrogen, due to its very good cooling capacity, could be applied in advanced engines as a cooling agent for turbine blades and disks [4].

Hydrogen have about four time lower energy density per unit volume (Tab. 1), what means that require four time more volume to storage the same energy content as kerosene. In addition, hydrogen needs to be stored in liquid state, under high pressure. Large volume cryogenic fuel tanks will change the conventional airframe configuration. Proper arrangement of cylindrical tanks for liquid hydrogen storage is very important due to aircraft centre of gravity localization. In accordance with reference [12], the best localization of cryogenic fuel tanks for long-range aircraft is fuselage. Aft part of fuselage and the front part between cockpit and passenger compartment is taking into consideration for such kind of aircraft.

Tab. 1. Comparison of hydrogen properties with conventional aviation fuel [4, 7]

Property	Unit	Hydrogen	Synjet
Heat of combustion	kJ/kg	120 000	42 800
Density at boiling point	kg/m^3	71	800
Flammability in air	vol%	4-75	0.8-6.0
Minimum ignition energy	MJ	0.02	0.25
Burning velocity	m/s	265	43
Autoignition temperature	ºC	585	440
Cooling capacity	MJ/kg	20.2	0.38-0.85

Utilization hydrogen in cryogenic form is the main hydrogen disadvantage. Cryogenic liquid is boiling and vaporize, so the tanks and fuel system need very good thermal insulation, to ensure the lowest losses due to evaporation. The mass of cryogenic container will be much higher than the mass of stored hydrogen. In addition, hydrogen condensation and storage in liquid form require a lot of energy. Minimum ignition energy and high flame speed are other hydrogen disadvantages. Because of low value of ignition energy, even a small spark has enough energy to ignite hydrogen. Wide burning limit may have negative consequences, because there exist a risk of ignition in a wide range of concentration [10].

Nowadays the production and utilization of kerosene is much cheaper so that makes hydrogen unprofitable from economic point of view, especially that in addition there is a lack of proper infrastructure. In spite of this, it should be taken into account that fuels used in aviation are produced from crude oil, which natural sources are not renewable. Due to the growing demand for energy, in the next few decades the depletion of natural sources of fossil fuel can be accepted.

3. Engine thermodynamic cycle analysis

Thermodynamic model of analysed turbofan engine was implemented in MATLAB software. Analysis was carried out for off-design point conditions (take-off) and design point conditions (cruise). The model consists off the blocks, which describe work of main turbofan engine components [5, 6, 9]. Input data necessary to carry out the thermodynamic cycle analysis, have been selected based on the analysis of available technical data for turbofan engines [8, 15, 16]. Based on the information about overall engine pressure ratio and fan pressure ratio, the pressure ratio of low-pressure compressor (LPC) and high-pressure compressor (HPC) have been obtained. Mass flow rate for design point conditions was establish by running the engine model with assumption that [15]:

$$Thrust_{cruise} \approx Thrust_{max}/4. \quad (1)$$

The working medium was modelled using a semi-perfect gas model. Properties of the exhaust gases were modelled based on the reference [6]. Turbine inlet temperature was assumed for take-off conditions as T_3 = 1750 K, and for cruise as T_3 = 1550 K [11]. Full expansion of working fluid in the fan nozzle and in the exhaust nozzle was assumed. Input parameters necessary to carry out the analysis of the engine thermodynamic cycle are listed in Tab. 2. Drop of turbine efficiency due to cooling process, was not taking into consideration in this study.

Tab. 2. Input data to analysis

Property		Unit	Take-off	Design point
Altitude	H	m	0	10668
Velocity of flight	Ma	–	0	0.85
Air mass flow	m	kg/s	670	350
Fan pressure ratio	π_F	–	1.65	1.65
Low pressure compressor ratio	π_{LPC}	–	1.60	1.60
High pressure compressor ratio	π_{HPC}	–	12.80	12.80
Overall pressure ratio	π	–	33.80	33.80
Bypass ratio	μ	–	4.40	4.40
Turbine inlet temperature	T_3	K	1750	1550

By the years is observed the trend in increasing temperature before turbine [5]. Material properties and advanced cooling systems for turbines blades allow for application higher turbine inlet temperature (TIT), which has a significant impact for increasing the specific thrust and thermal efficiency of the engine as well as for reduction of specific fuel consumption (SFC) [5]. The TIT limit for uncooled engines is adopted at the level of 1350 K [9]. If this value is exceed, it is recommended to use cooling systems for turbine assembly. The conventional source of coolant fluid is air delivered from high-pressure compressor (HPC). Delivered air for cooling purpose, it decreases the amount of core air that supplied the combustion chamber. The energy balance of the combustion chamber (Fig. 1) leads to the equation for fuel-to-air ratio [5].

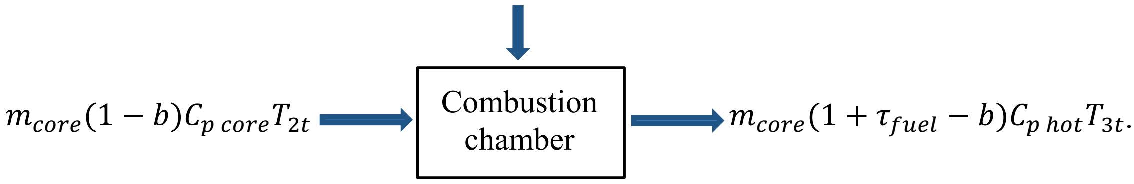

Fig. 1. Combustion chamber energy balance

Fuel-to-air ratio relation from combustion chamber balance with taking into consideration cooling bleed extracted from the compressor [5]:

$$\tau_{fuel} = \frac{(1-b)\cdot(C_{p\,hot}\cdot T_{3t} - C_{p\,cold}\cdot T_{2t})}{\eta_{cc}\cdot Q_{hv} - C_{p\,hot}\cdot T_{3t}}, \tag{2}$$

where:
b – cooling bleed,
T – total temperature at given engine section,
$C_{p\,hot}$ – specific heat of hot gases,
$C_{p\,cold}$ – specific heat of air,
η_{cc} – combustion chamber efficiency,
Q_{hv} – fuel heating value.

Temperature at the outlet of the HPT was calculated from the energy balance for high-pressure spool, in accordance with the following relation [5]:

$$P_{HPC} = \eta_m \cdot P_{HPT}, \tag{3}$$

where:
P_{HPC} – power of high-pressure compressor,
P_{HPT} – power of high-pressure turbine,
η_m – mechanical efficiency.

From the relation (3), the temperature at the outlet of the HPT is defined as [5]:

$$T_{3at} = T_{3t} - \frac{P_{HPC}}{\eta_m \cdot m_{core}\cdot (1+\tau_{fuel}-b)\cdot C_{p\,hot}}, \tag{4}$$

where:
m_{core} – air mass flow passing through the main core of the engine.

Information about amount of bleed delivered from the HPC for cooling purpose, are presented in Tab. 3.

Tab. 3. Cooling bleed

	Take-off		Cruise	
cooling bleed [%]	Kerosene	LH2	Kerosene	LH2
HPT	15	15	2.5	2.5
LPT	–	3	–	–

Thrust force generated by turbofan engine can by expressed by the relation [5]:

$$K = m_{core} \cdot \mu \cdot (V_{fan} - V) + m_{core} \cdot [(1 + \tau_{fuel} - b) \cdot V_{core} - V], \tag{5}$$

where:

μ – bypass pressure ratio,
V_{fan} – velocity of bypass air (fan nozzle),
V – flight speed,
V_{core} – velocity of exhaust gases.

4. Results discussion

Engine fuelled by liquid hydrogen during the take-off conditions requires more intensive cooling of turbines than engine fuelled by kerosene. In case of applying kerosene fuel, 15% of bleed was used to reduce HPT temperature to permitted TIT limit. In case of implementation hydrogen fuel 15% of cooling bleed was insufficient, to meet the temperature requirements. Because of too high temperature before low-pressure turbine, it was necessary to apply low-pressure turbine cooling. For this purpose, additional 3% of compressor delivered air was used. During the cruise, condition high-pressure turbine was cooling by 2.5% of delivered air, for both cases of implemented fuel. It was not necessary to cool the LPT.

Replacement conventional aircraft fuel by hydrogen, exert evident influence on researched turbofan engine performance that are presented in Tab. 4.

Tab. 4. Engine performance

			Take-off		Cruise	
			Kerosene	LH_2	Kerosene	LH_2
Specific thrust	kj	[Ns/kg]	369.42	423.04	231.49	275,21
SFC	cj	[kg/Ns]	$0.99507 \cdot 10^{5}$	$0.37101 \cdot 10^{-5}$	$1.8143 \cdot 10^{-5}$	$0.69727 \cdot 10^{-5}$
Engine thrust	K	[kN]	247.51	283.44	81.02	96,32
Fuel-air-ratio	τ_fuel	-	0.02340	0.01030	0.02330	0.01060
Fuel mass flow	m_{fuel}	[kg/s]	2.46	1.05	1.47	0.67
Exhaust mass flow	m_{hot}	[kg/s]	107.93	102.79	64.66	63.87
Fan power	P_{FAN}	MW	32.25		14.64	
HPC power	P_{HPC}	MW	6.66		3.02	
LPC power	P_{LPT}	MW	58.20		26.61	
Velocity of exhaust gases	V_{core}	m/s	720.94	1107.10	924.36	1175.70
Velocity of bypass air	V_{fan}	m/s	310.27		383.72	

Substitution of conventional aviation fuel with alternative fuel, allow increasing engine thrust during take-off by 14.5%, with simultaneous reduction of specific fuel consumption by 62.7%. Fuel mass flow was decreased by 57.3% and mass flow of hot exhaust gases was decreased by 4.8%. The velocity of exhaust gases is by 53.6% higher for hydrogen-fuelled aircraft, than for aircraft supplied by kerosene. Similar trend was observed as well for cruise condition, where engine thrust increased by 18.9% for hydrogen fuel, and SFC was decreased by 61.6%. Fuel mass flow was decreased by 54.3% and mass flow of hot exhaust gases decreased slightly. The percentage increase in velocity of exhaust gases is 27.2%.

The reduction in SFC is significant for both analysed flight conditions, which makes the hydrogen-fuelled engine more economical than kerosene. The higher exhaust gases velocity is responsible for engine thrust increase, expressed by the equation (5). SFC is the ratio of fuel mass to the engine thrust. Application of hydrogen is accompanied by fuel mass reduction and increase in the engine thrust; therefore, these two factors determine the reduction of SFC. Due to hydrogen large heat of combustion, the value of fuel-to-air ratio is lower than for kerosene, which implies lower fuel consumption. The larger exhaust gases velocity from the main core for engine fuelled by hydrogen is caused by the higher gas temperature and pressure at the outlet of LPT (Fig. 3). Increase of these two parameters, influence directly on velocity of hot stream, which exert positive effect for engine thrust, but too large speed of exhaust gases may be undesirable from environmental point of view, as it affects the increase of noise emitted by turbine engines.

Turbofan engine scheme with marked characteristic cross-sections is presented on Fig. 2. More detailed results of conducted analysis are discussed for take-off conditions as the most critical stage of the flight.

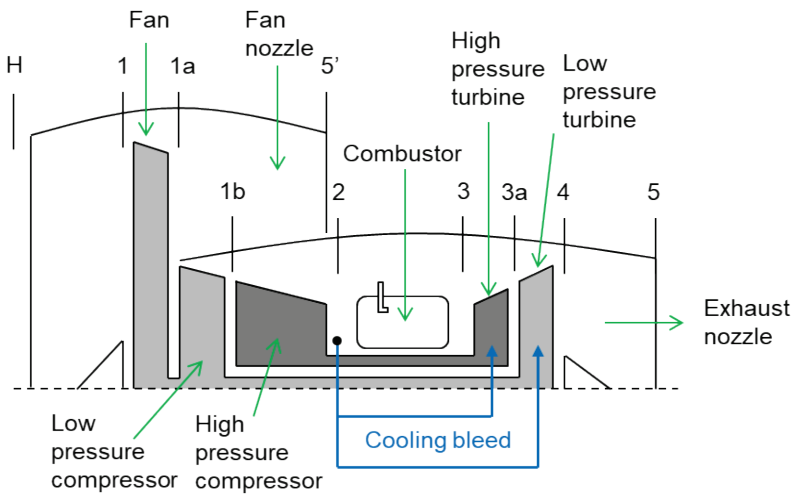

Fig. 2. Turbofan engine scheme

The temperature and pressure distribution in particular engine section is presented for off-design point conditions on Fig. 3. The bottom horizontal axis describes the engine control sections related to the main engine core, while the top horizontal axis is related to the external engine core sections.

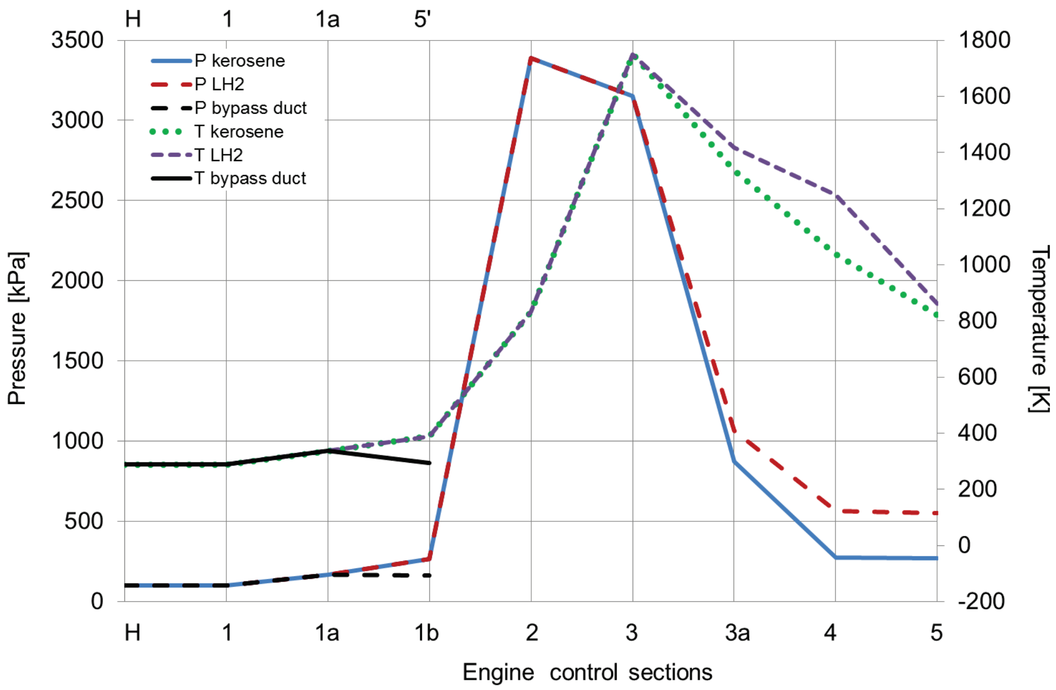

Fig. 3. Pressure and temperature distribution – take off conditions

The specific thrust and specific fuel consumption dependency on engine pressure ratio was presented for take-off conditions on Fig. 4. Specific thrust and specific fuel consumption are the most important parameters that specified turbine engine performance.

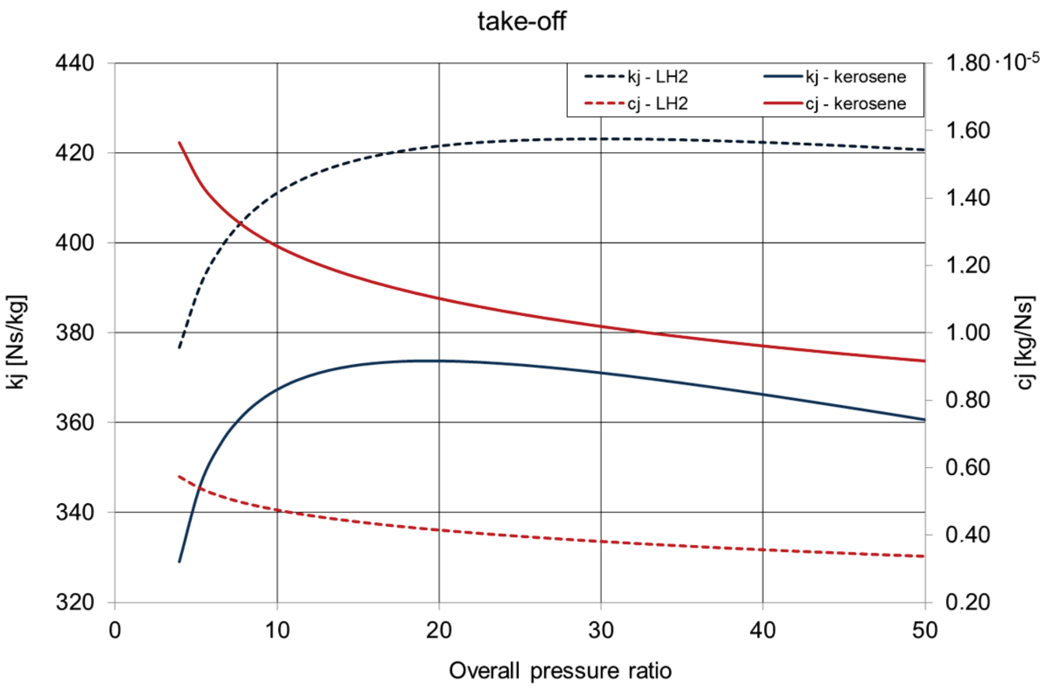

Fig. 4. Specific thrust and specific fuel consumption in function of engine pressure ratio

For engine supplied by hydrogen fuel, higher specific thrust values are obtained with simultaneously lower SFC values for take-off, in comparison with kerosene. The maximum of specific thrust, in case of hydrogen fuel, is offset in the direction of higher values of engine pressure ratio. The optimal pressure ratio is equal 30.36 for hydrogen fuel, whereas for kerosene 19.9. The dependence of SFC on the engine thrust is a decrease function for both implemented fuels.

5. Conclusion

Hydrogen implementation will allow long term grow of aviation without interfering with the natural environment and would allow for independence from natural sources of fossil fuels. The results of carried out analysis demonstrate the positive influence of selected alternative fuel on turbofan engine performance. The more effective cooling system should be taken into consideration. The solution of this problem could be application of heat exchanger to cooling the delivered compressor bleed air [3]. It will reduce the compressor delivery air as well as improve engine performance. In addition, hydrogen could be taken into account as coolant used in engine hot section.

Conducted analysis can be introduction to more advanced analyses of hydrogen fuelled engine thermodynamic cycle. At the level of further analysis, it is worth considering the possibility of using other alternative fuels in aviation transport.

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