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# The impact of thermodynamics parameters of turbofan engine with ITB on its performance

*Presented paper is focused on the influence of additional combustor chamber named inter turbine burner on turbofan engine unit parameters. Investigation has been made how changing selected engine parameters affect its performance. A comparison has been made between the baseline turbofan engine and the engine with ITB. Engine thermodynamics model was prepared in MATLAB software. Main combustion chamber was fueled by kerosene, commmonly used in aviation transport, while inter turbine burner by alternative fuel. As an alternative fuel were choose liquid hydrogen and methane. Numerical researches were carried out for take-off conditions. Engine specific thrust and specific fuel consumption were obtained as a function of bypass ratio, turbine inlet temperature, fan pressure ratio, HPC and LPC pressure ratio. The results of the study indicate that hybrid engine with additional combustion chamber fueled by hydrogen fuel is more efficient than other studied cases.*

Key words: *inter turbine burner, turbofan engine, liquid hydrogen, alternative fuels*

## 1. Introduction

Due to the problems with global warming and air traffic increasing, future aircraft engines should be characterized by low pollutant emissions and high reliability. At the same time, low combustion emission should be accompanied by high efficiency of the combustion process. Emission from aircraft engines cannot be ignored, because aircrafts emit their pollutants in upper layers of atmosphere what may have stronger impact on environmental destruction than on the ground. Nowadays aviation industry is responsible for approximately 2% of global emissions of $CO_2$ generate by the human [19]. Therefore due to the dynamical development of air transport, environmental protection is the key issue, especially that it is forecast that air travel will double over the next two decades [19].

Advisory Council for Aviation Research and Innovation in Europe (ACARE) present the highly ambitious goals within a framework of FlightPath 2050. Assumption has been made that in 2050 year allowable technologies permit for reduction of $CO_2$ emission per passenger kilometer by 75% and for reduction of $NO_x$ emission by 90%. The ACRAE assume also no emissions during aircraft taxiing, air vehicles recyclability and the Europe leadership in atmospheric researches [18].

Existing aircraft technologies are not sufficient to significantly reduce $CO_2$ emission and other harmful products of combustion process. The solution of this problem will be development new alternative propulsion systems and energy sources [19].

Due to depletion of fossil fuels it is anticipated that application of non-conventional fuels will be significant. In the first place application will find synthetic fuels (GTL-gas to liquid, CTL-coal to liquid) and biofuels [14]. Because nowadays fossil fuels are extensively use by all means of transport which translates into a significant increase in the carbon dioxide content in the atmosphere. Carbon dioxide is a product of chemical reaction of hydrocarbon fuel combustion and may be eliminated by application non-carbon fuel. In this case non-carbon fuel like liquid hydrogen or fuels with a low carbon content, like methane, may be taken into consideration. Some potential pathways of aviation fuel evolution are presented on Fig. 1.

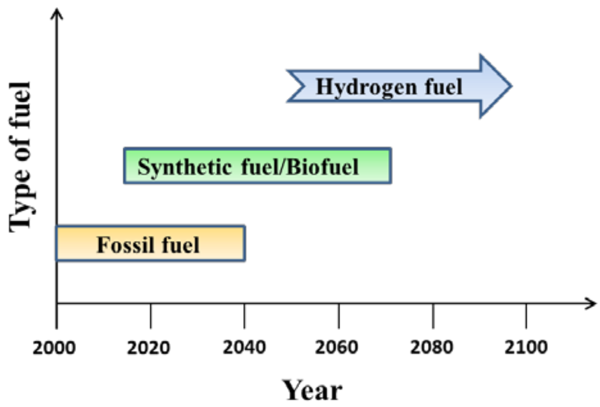


Fig. 1. Aviation fuels of the future [14]

The solution of the presented problem related to emission of harmful combustion product, will be new engine concept adapted to burn alternative fuel, characterized by higher engine efficiency.

To reduce turbine engine fuel consumption new engine concept with ITB is presented by [6–8, 11, 14–17]. Application of such conception allow for high pressure turbine inlet temperature reduction and accompanied $NO_x$ reduction. The ITB conception permit for application flameless combustion technique, which reduce the $NO_x$ considerable [6, 10, 16]. Flameless oxidation is a process which based on dilution of oxygen contained in the reactant stream and raising its temperature above the auto ignition temperature. Fuel oxidation is currently mainly used in industrial application [5, 6].

The ITB conception is also known as the reheat cycle. In such cycle gases expanded in HPT are reheated before the next expansion process that occur in LPT. In ITB fuel is burned at higher pressure than in conventional afterburner applied in turbine engines. That guarantee better engine thermal efficiency [13].



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Hydrogen has got wider flammability limit than kerosene so the combustion process can take place at lean conditions to reduce $NO_x$ emission [17]. $NO_x$ emission increases with fuel to air ratio and with the temperature of combustion process [12]. Nitrogen oxides are formed during the oxidation of nitrogen contained in the air exposed to high temperatures [12]. The main parameters that are responsible for nitrogen oxide formation are the flame temperature, the nitrogen and oxygen content and the residence time of the gases in the combustion zone. Reduction of these parameters would allow for $NO_x$ reduction, emitted by the aircraft turbine engines [2, 12].

Hydrogen is clean energy carrier [1] that require large fuel tanks due to the four time lower energy density per unit volume than kerosene. This hydrogen property will affect considerably the airframe configuration. This problem can be resolve by development of new aircraft type, namely the Blended Wing Body [11, 14]. BWB is resemble to flying wing [20]. This hybrid shape seems to be the most suitable for large hydrogen cylindrical tanks [14].

Another promising alternative fuel next to hydrogen is Liquid Natural Gas. LNG in 90% consist of methane. The remaining 10% are small fractions of liquid ethane, propane, nitrogen and other impurities. LNG is a cryogenic fluid like hydrogen. Application of LNG will allow for a 20% reduction in $CO_2$ emission. Further reduction is possible by adding liquid biomethane to the LNG, to create Bio-LNG [3]. Studies on cryogenic alternative fuels bring to the conclusion that fuel tanks should be placed within the fuselage [3].

## 2. Inter turbine burner concept

In conventional turbofan engine fuel is burn in main combustion chamber and then hot gases are expand through the turbine. In turbofan engine configuration with inter turbine burner combustion is continued in additional combustion chamber, situated between high pressure turbine (HPT) and low pressure turbine (LPT). The main goal of this conception is to increase engine efficiency and specific thrust [8, 16]. The ITB as an additional source of heat influence on increase of power output for a given engine size. In accordance with [16] the specific fuel consumption (SFC) is lower than for engine with afterburner due to the fact that operating pressure of an ITB is higher and it help to improve the thermal efficiency of the Brayton cycle [16].

The turbofan engine configuration with marked engine stations is presented on Fig. 2.

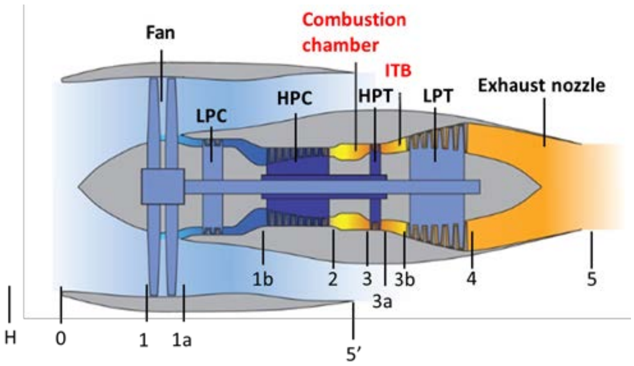


Fig. 2. Turbofan engine configuration with ITB [14]

Description of sections numbers presented on Fig. 2: H – ambient conditions, 0 – inlet conditions, 1 – conditions at the fan inlet, 1a – conditions at the LPC inlet, 1b – conditions at the HPC inlet, 2 – conditions at the combustion chamber inlet, 3 – conditions at the HPT inlet, 3a – condition at ITB inlet, 3b – conditions at the LPT inlet, 4 – conditions at the LPT outlet, 5 – conditions at the exhaust nozzle outlet, 5'– conditions at the cold nozzle outlet.

## 3.Turbofan engine numerical model

The thermodynamics model of turbofan engine with dual combustor chamber was implemented in Matlab software and is described in detail in references [9]. A twin spool configuration of engine is considered, where the high pressure compressor (HPC) is driven by the high pressure turbine (HPT), whereas the fan and low pressure compressor (LPC) are driven by low pressure turbine (LPT). Engine performance analysis was carried out for off-design conditions. Working fluid was describe as semi-perfect gas [9]. Engine operating conditions are presented in Table 1.

Table 1. Operating conditions

| Description | Notation | Unit | Take-off |
|---|---|---|---|
| Mach number | Ma | – | 0 |
| Altitude | H | m | 0 |
| Air mass flow | $\dot{m}$ | kg/s | 670 |
| Fan pressure ratio | FPR | – | 1.65 |
| Bypass ratio | BR | – | 4.4 |
| LPC pressure ratio | $\pi_{LPC}$ | – | 1.6 |
| HPC pressure ratio | $\pi_{HPC}$ | – | 12.8 |
| HPT turbine inlet temperature | $TIT_{HPT}$ | K | 1500 |
| LPT turbine inlet temperature | $TIT_{LPT}$ | K | 1300 |

Engine numerical model consist of blocks that describe the work of individual engine components like: inlet, fan, low pressure compressor, high pressure compressor, combustion chamber, high pressure turbine, inter turbine burner, low pressure turbine, exhaust nozzle and bypass. The scheme of numerical model is presented on Fig. 2. Prepared thermodynamics model do not taking into consideration turbine cooling process.

The design of turbofan engine is a compromise between turboprop and turbojet engines. This construction is characterized by the occurrence of two streams of air [4]. In the analyses case, the air in primary core (hot stream) goes through the fan, low pressure compressor, high pressure compressor, combustor chamber, high pressure turbine, low pressure turbine, inter turbine burner, low pressure compressor and exhaust nozzle. The second part of air (cold stream) goes through fan and then to the outer duct ended by the "cold" nozzle.

Bypass ratio is defined as:

$$\mathrm{BR} = \frac{\dot{m}_c}{\dot{m}_h} \tag{1}$$

where: $\dot{m}_c$ – mass flow rate through the bypass, $\dot{m}_h$ – mass flow rate through the primary engine core.

High-bypass pressure ratio turbofan engines found application in large commercial aircraft, as much fuel efficient than other types of turbine engines [4]. The variation of BR influence directly variation in engine components diameters and rotational speed [12].

There are two fundamental indicators that define the performance of turbine engines – specific thrust and specific fuel consumption. Specific thrust is the engine thrust per mass flow rate:

$$ST = \frac{T}{\dot{m}_h} \quad (2)$$

Specific fuel consumption is defined as the fuel mass flow rate per unit thrust and can be expressed by following equation:

$$SFC = \frac{m_{fuel\_1} + m_{fuel\_2}}{T} \quad (3)$$

where: $m_{fuel\_1}$ – fuel burn in main combustion chamber, $m_{fuel\_2}$ – fuel burn in ITB.

In analysis case, the fuel flow rate is the sum of the fuel flow related to the main combustion chamber and the fuel flow related to the ITB.

Engine thrust force for turbofan engine with ITB:

$$T = \dot{m}_h BRV_5' + \dot{m}_h(1 + f + f_{tb})V_5 - \dot{m}_h(1 + BR)V \quad (4)$$

where: $\dot{m}_h$ – mass flow rate (main gas path), BR – bypass ratio, $V_5'$ – velocity of bypass air, $V_5$ – velocity of hot gases, f – fuel to air ratio, $f_{tb}$ – fuel to air ratio for turbine burner, V – velocity of the flight.

The presented block structure of the engine numerical model (Fig. 2), illustrate the order of performed calculations.

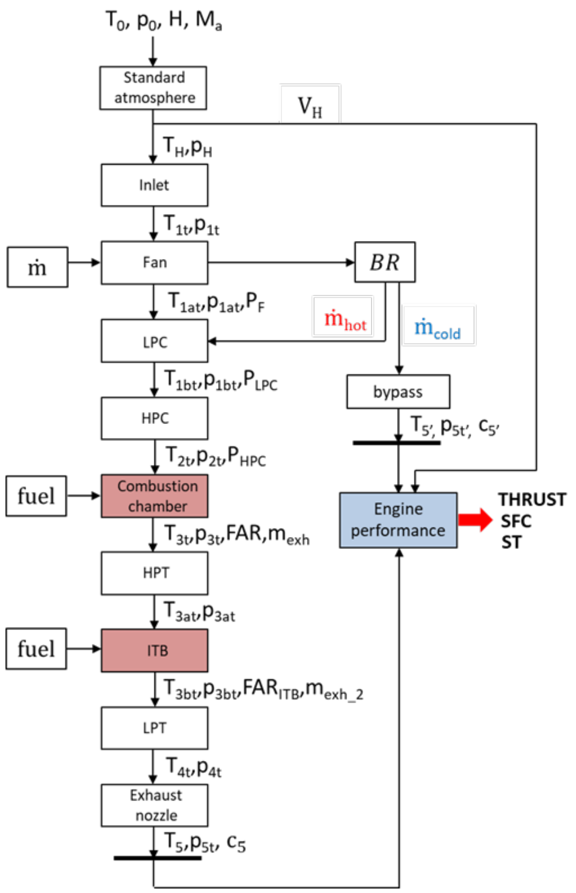


Fig. 2. The schematic of numerical model of turbofan engine with ITB in Matlab software

The model was developed based on the basic thermodynamics relations [4, 9, 12]. Prepared model allow analyze the performance of hybrid turbofan engine.

Turbofan engine performance are influence by the following thermodynamics parameters:

– bypass pressure ratio,
– fan pressure ratio,
– overall pressure ratio,
– turbine inlet temperature.

Low specific fuel consumption is achieve by continuously increasing the overall pressure ratio (OPR), and bypass ratio (BR) [16]. Turbine inlet temperature is the most important design parameter that influence thermodynamic cycle of turbine engine [4]. For a conventional turbine engine, the HPT inlet temperature is a design variable. In case of engine configuration with ITB, both the HPT and LPT inlet temperatures are design variables [16].

## 4.Scope of the work

The main scope of presented work is analysis how variation of selected engine parameters influence engine performance. Numerical analysis was carried out for take-off conditions. As the variable parameters were choose: bypass ratio, turbine inlet temperature, fan pressure ratio, HPC and LPC pressure ratio. Performance comparison was made between hybrid engine with ITB and baseline turbofan engine.

Two options of engine feeding were taken into consideration. In first case assumptions has been made that main combustion chamber is fueled by kerosene while the ITB is fueled by liquid hydrogen. In second case the main combustion chamber is invariable fueled by kerosene while ITB by liquid methane.

It can be seen in Fig. 6 to Fig. 14 that researches was carried out for three values of bypass ratio: 4.4, 6 and 8.

Thermodynamics calculations were carried out in order to determine the flow parameters at characteristic engine sections (Fig. 2) and to calculate specific thrust and specific fuel consumption.

## 5.Result discussion

The variations of engine performance with selected thermodynamics parameters changes are presented on Fig. 3 to Fig. 14.

The relation between bypass ratio (BR) and engine specific thrust (ST) is presented on Fig. 3.

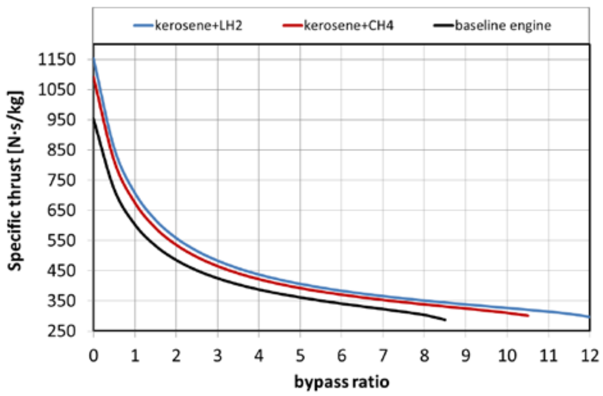


Fig. 3. Bypass ratio vs. specific thrust

The graph shows the decreasing dependence of the specific thrust with the increase of engine BR (Fig. 3). BR is relation between cold stream of air and the air in the main engine core, described by equation (1). If the BR increase, more air goes through the outer duct, what affect significantly the increase in engine outer diameter. This issue cause the drag increase as well as reduction of ground clearance [14].

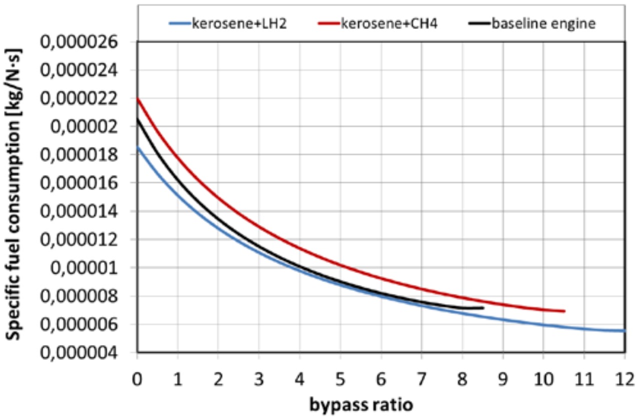


Fig. 4. Bypass ratio vs. specific fuel consumption

It can be seen on Fig.4, that increasing the BR improves the specific fuel consumption at the expense of specific thrust decrease. The lowest value of SFC is obtained for engine with inter turbine burner fueled by liquid hydrogen (Fig. 4). At the same time, for this case the highest specific thrust was received (Fig. 3). In addition for a given working conditions, the highest values of BR are possible to applied for engine configuration with inter turbine burner fueled by hydrogen. Analyzing the chart on Fig. 3 and Fig. 4 it can be seen that for an accepted operating conditions wider range of bypass ratio can be implemented for turbofan engine with additional combustor chamber. For hydrogen fueled ITB this range is wider than for methane.

Figure 5 present the variation of engine specific thrust with the changes of high pressure turbine inlet temperature ($TIT_{HPT}$).

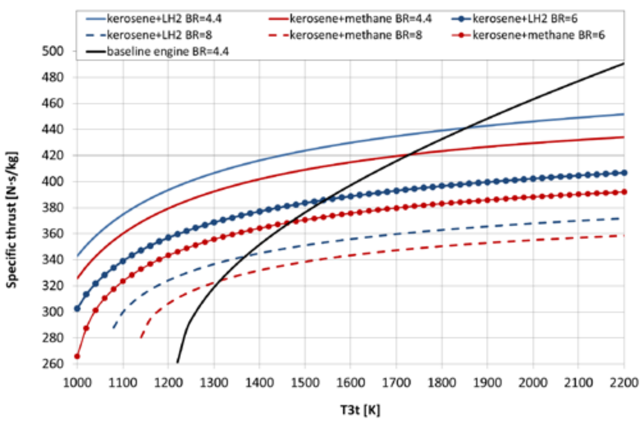


Fig. 5. $TIT_{HPT}$ vs. specific thrust

Growth of the $TIT_{HPT}$ cause the increasing of engine specific thrust (Fig. 5). It is noticeable that for baseline turbofan engine, thrust increase with the $TIT_{HPT}$ is quicker than for modified construction. In case of an engine with ITB, for lower inlet turbine temperatures higher values of ST are obtained in comparison to the baseline engine. This will significantly reduce emission of $NO_x$ with simultaneous ensuring better engine performance. In addition temperature reduction will increase engine component life. The value of turbine inlet temperature is a design variable and is limited by material properties.

Increase in BR value result in lower specific thrust value attained by the power plant as well as lower SFC (Fig. 6).

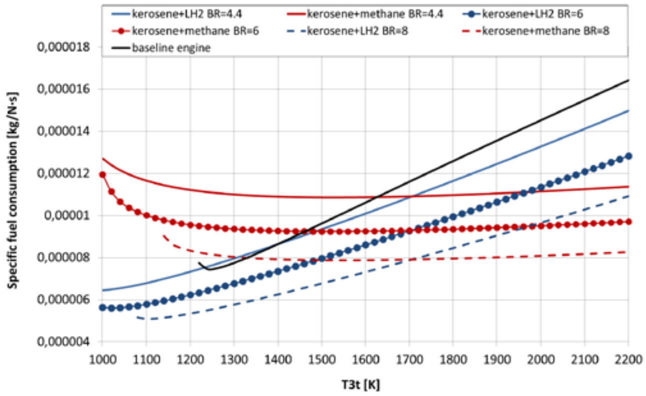


Fig. 6. $TIT_{HPT}$ vs. specific fuel consumption

Application of alternative fuel in additional combustion chamber exert evident effect on variation of specific fuel consumption with the $TIT_{HPT}$ changes (Fig. 6). For liquid hydrogen SFC show upward trend while for methane the graph is decreasing to a minimum at temperature about 1520 K, and then slowly increases.

For turbine inlet temperatures higher than 1700 K, the power plant with additional combustor chamber fueled by methane remains more economical than engine with ITB fueled by hydrogen and baseline engine (Fig. 6).

Figure 7 represents the relation between the specific thrust and low pressure turbine inlet temperature. The shape of the graph demonstrates the increase of engine specific thrust with low pressure turbine inlet temperature increase. Application of higher values of BR results in a reduction of specific thrust.

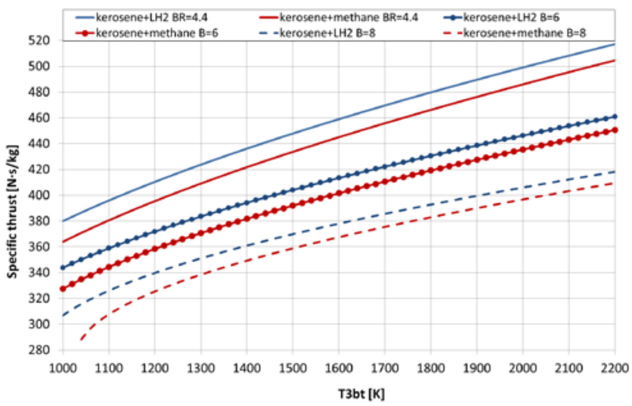


Fig. 7. $TIT_{LPT}$ vs. specific thrust

The decrease of ST with the growth of BR is accompanied by a reduction of specific fuel consumption (Fig. 8).

The graph on Fig. 8 depict that the growth of SFC for modified engine supplied by methane is much rapid than for hydrogen.

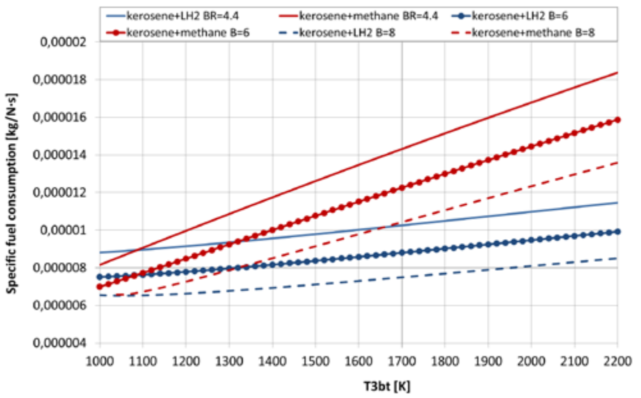


Fig. 8. $TIT_{LPT}$ vs. specific fuel consumption

The relation between the fan pressure ratio and engine performance is presented on Fig. 9 to Fig. 10.

For the engine with an additional combustion chamber, the specific thrust as a function of fan pressure ratio is increasing relationship (Fig. 9), while the specific fuel consumption is decreasing (Fig. 10). Application of hydrogen or methane in additional combustor chamber exert visible influence on engine specific thrust in comparison to the baseline engine.

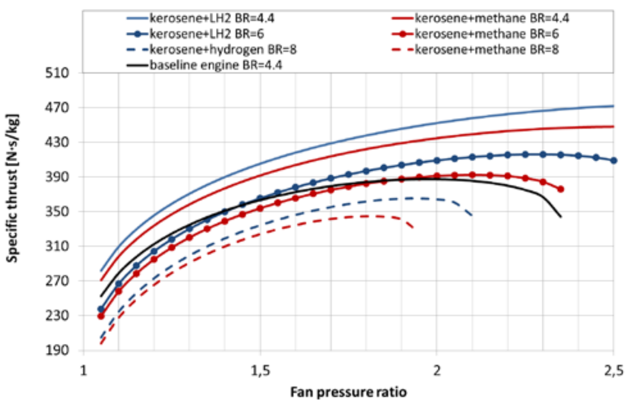


Fig. 9. Fan pressure ratio vs. specific thrust

With the growth of bypass ratio, shorter range of fan pressure ratio (FPR) can be implemented as well as lower values of specific thrust (Fig. 9) and SFC (Fig. 10) are obtained. It can be seen on Fig. 9 that the optimum of FPR decrease with increase in BR.

The course of the specific fuel consumption as a function of fan pressure ratio for the baseline engine is similar to the engine with ITB fueled by hydrogen (Fig. 10).

The engine performance parameters in function of HPC pressure ratio are presented on Fig. 11 and Fig. 12.

The graph on Fig. 11 shows that ST increase with HPC pressure ratio to achieve the maximum, and then slowly go down. For hydrogen fuel, the optimal pressure ratio is about 21 while for methane fuel about 22. For baseline engine optimal pressure ratio is about 18. SFC has a decreasing tendency (Fig. 12). For hydrogen fueled ITB the highest values of ST are obtained with simultaneous the lowest SFC. Comparing the SFC for conventional turbofan engine and hybrid engine fueled by methane, it is noticeable that for HPC pressure ratios up to about 26, the lowest values of SFC are obtained for modified engine configuration. Opposite situation is observed for HPC pressure ratios higher than 26. The SFC curve for conventional engine is much steep while for engine with ITB fueled by methane much flatten (Fig. 12).

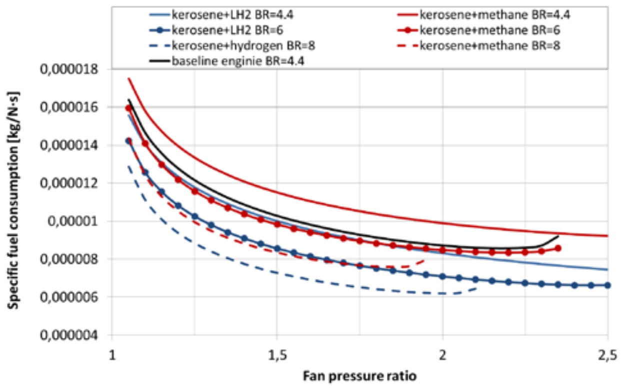


Fig. 10. Fan pressure vs. specific fuel consumption

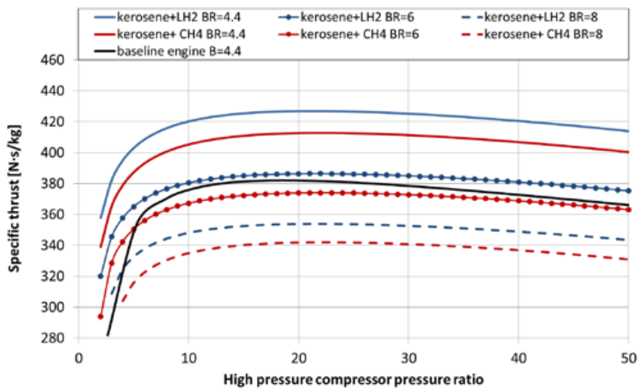


Fig. 11. HPC pressure ratio vs. specific thrust

Increasing the compressor pressure ratio (as well as overall engine pressure ratio) result in longer and heavier engine construction.

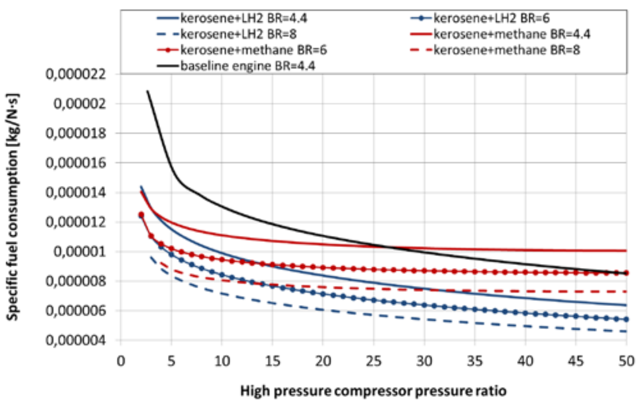


Fig. 12. HPC pressure ratio vs. specific fuel consumption

The variation of engine ST and SFC with LPC pressure ratio increase is presented on Fig. 13 and Fig. 14 respectively. Higher specific thrust values are achieved by the hybrid engine. Better performance are obtained for hybrid configuration adapted for burning hydrogen fuel (Fig. 13 and Fig. 14). It is noticeable that ST determined for baseline configuration, decrease more rapid with the growth of the LPC pressure ratio than for configuration with ITB.

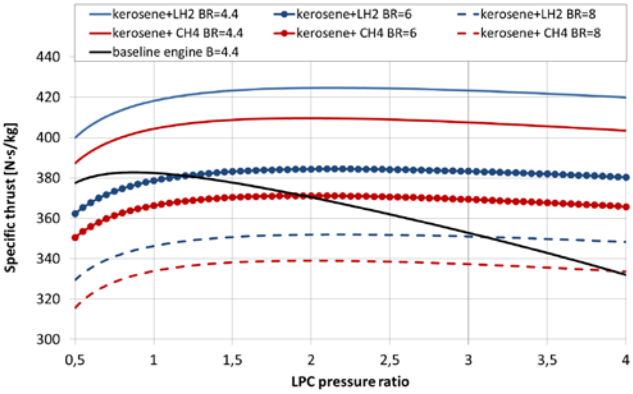


Fig. 13. LPC pressure ratio vs. specific thrust

The graph presented on Fig. 14 shows that the more efficient SFC curves were obtained for engine with hydrogen fueled ITB.

The SFC curve that present the baseline turbofan engine has got similar course like for hybrid engine with combustor chamber adapted for hydrogen fuel (Fig. 14).

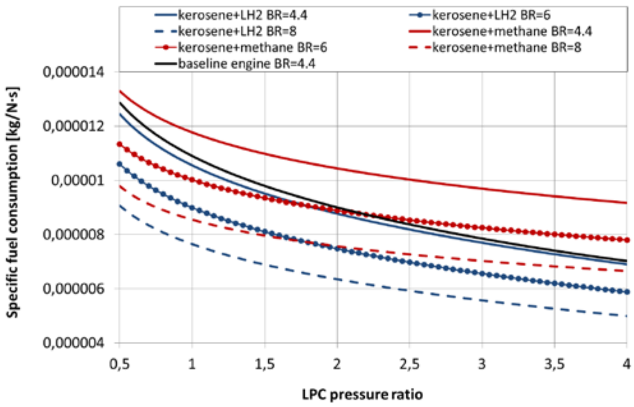


Fig. 14. LPC pressure ratio vs. specific fuel consumption

## 6. Summary

The significant influence on specific thrust and specific fuel consumption value has got not only a choice of alternative fuel burned in additional combustor chamber but also selection of appropriate turbine engine operating parameters. Presented work is focused on conception of turbofan engine with ITB fueled by alternative fuel – hydrogen or methane, while the main combustion chamber is supply by kerosene. Studies devoted by the scientist on ITB application in turbine engines are mostly focused on the case in which the main combustion chamber is fueled by liquid hydrogen, while second combustion chamber by biofuel or kerosene. The advantage of the adopted and presented in this paper conception is less complexity of the engine and airframe assembly. Such solution will be cheaper and easiest to implementation than application hydrogen as a fuel dedicated to the main combustion chamber. In addition application of ITB fueled by hydrogen will provide valuables data to the further researches on hydrogen fueled aircraft.

Based on analysis of the presented results, better from a performance point of view presents the engine with additional combustion chamber fueled by hydrogen. Conducted analysis indicate the possibility to reduce turbine inlet temperature significantly for engine configuration with ITB, what will permit for reduction of $NO_x$ emission. The temperature depression result also in lengthen engine overhaul life. Generally the reduction in TIT cause the reduction in engine thrust but also in specific fuel consumption. In case of hydrogen fueled ITB the reduction in SFC is considerable than in case of methane fuel. Lower fuel consumption makes engine more economical, which is very important engine attribute that determines the choice of a given power plant and affect the range of the aircraft.

Presented advantages of using hydrogen as a fuel make the proposed hybrid engine concept very promising for future aviation.

Presented results come from the numerical simulations of engine thermodynamic cycle. Model has been elaborated based on the basic thermodynamics equations. The written code is able to predict the turbofan engine performance. Elaborated numerical model of hybrid turbofan engine require validation with data obtained during the experimental researches, conducted on the engine prototype. Model should be adjusted to the experimental data and then used for more detailed analysis. This type of advanced experimental researches are the domain of manufacturers of the largest aircraft engines and definitely go beyond the scope of the available laboratory.

## Nomenclature

| | |
|---|---|
| BR | bypass ratio |
| BWB | blended wing body |
| CTL | coal to liquid |
| FAR | fuel to air ratio |
| GTL | gas to liquid |
| HPC | high pressure compressor |
| HPT | high pressure turbine |
| ITB | inter turbine burner |
| LNG | liquid natural gas |
| LPC | low pressure compressor |
| LPT | low pressure turbine |
| OPR | overall pressure ratio |
| SFC | specific fuel consumption |
| ST | specific thrust |
| T | engine thrust |
| TIT | turbine inlet temperature |

## Bibliography


[1] AL-BAGHDADI, M. An overview of hydrogen as an alternative fuel. *Encyclopedia 2020*. https://doi.org/10.32545/encyclopedia202006.0003.v1

[2] BOYCE, M.P., Gas turbine engineering handbook. *Butterworth-Heinemann*. Fourth edition, 2012.

[3] BURSTON, M., CONROY, T., SPITERI, M. et al. Conceptual design of sustainable liquid methane fuelled passenger aircraft. *20th ISPE International Conference on Concurrent Engineering*. 2013. https://doi.org/10.3233/978-1-61499-302-5-391

[4] EL-SAYED, A.F. Aircraft propulsion and gas turbine engines. *CRC Press*. 2017.

[5] GUTHE, F., HELLAT, J., FLOHR, P. The reheat concept: the proven pathway to ultra-low emissions and high efficiency and flexibility. *ASME Turbo Expo 2007: Power for Land, Sea and Air*. 2007, Montreal.

[6] LEVY, Y., ERENBURG, V., SHERBAUM, V. et al. Development of combustor for a hybrid turbofan engine. *International Journal of Turbo and Jet Engines*. 2019. https://doi.org/10.1515/tjj-2019-0042

[7] LIEW, K.H., URIP, E., YANG, S.L. et al. Performance cycle analysis of turbofan engine with interstage turbine burner. *Journal of Propulsion and Power*. 2006, **22**(2). https://doi.org/10.2514/1.13394

[8] LIU, F., SIRIGNANO, W.A. Turbojet and turbofan engine performance increase through turbine burners. *Journal of Propulsion and Power*. 2001, **17**(3). https://doi.org/10.2514/2.5797

[9] MARSZAŁEK, N. Performance analysis of turbofan engine with additional combustion chamber fueled by alternative fuel. *Combustion Engines*. 2019, **179**(4), 249-253. https://doi.org/10.19206/CE-2019-441

[10] PERPIGNAN, A.A.V., RAO, A.G. Effects of chemical reaction mechanism and $NO_x$ formation pathways on an inter-turbine burner. *The Aeronautical Journal*. 2019, **123**(1270), 1898-1918. https://doi.org/10.1017/aer.2019.12

[11] RAO, A.G., YIN, F., van BUIJTENEN, J.P. A hybrid engine concept for multi-fuel blended wing body. *Aircraft Engineering and Aerospace Technology*. 2014, **86**(6), 483-493. https://doi.org/10.1108/AEAT-04-2014-0054

[12] SARAVANAMUTTO, H., ROGERS, G., COHEN, H. et al. Gas turbine theory. *Pearson Prenticle Hall*. England 2009.

[13] SIRIGNANO, W.A., LIU, F. Performance increases for gas-turbine engines through combustion inside the turbine. *Journal of Propulsion and Power*. 1999, **15**(1), 111-118. https://doi.org/10.2514/2.5398

[14] TANG, K., RAO, A.G., van BUIJTENEN, J.P. Conceptual study of a hybrid turbofan engine with inter turbine burner. *Proceedings of the ASME Turbo Expo 2010*. ASME. 2010, 239-248. ASME. https://doi.org/10.1115/GT2010-22719

[15] VOGELER, K. The potential of sequential combustion for high bypass jet engines. *Proceedings of the International Gas Turbine and Aeroengine Congress and Exhibition*. 1998. https://doi.org/10.1115/98-GT-311

[16] YIN, F., RAO, A.G. Off-design performance of an interstage turbine burner turbofan engine. *Journal of Engineering for Gas Turbines and Power*. 2017. https://doi.org/10.1115/1.4035821

[17] YIN, F., RAO, A.G., van BUIJTENEN, J.P. Performance characteristic of a multi-fuel hybrid engine. *Proceedings of the ASME Turbo Expo 2013: Turbine Technical Conference and Exposition*. Volume 2: Aircraft Engine; Coal, Biomass and Alternative Fuels; Cycle Innovations. San Antonio, Texas 2013. ASME. https://doi.org/10.1115/GT2013-946012012

[18] https://www.acare4europe.org

[19] https://www.airbus.com/company/sustainability/environment/decarbonisation.html

[20] https://www.nasa.gov/centers/langley/news/factsheets/FS-2003-11-81-LaRC.html



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