Proceedings of ASME Turbo Expo 2013
GT2013
June 3-7, 2013, San Antonio, Texas, USA

GT2013-94601

PERFORMANCE CYCLE ANALYSIS FOR A MULTI-FUEL HYBRID ENGINE

Feijia Yin
Arvind G. Rao*
Jos P. van Buijtenen
Faculty of Aerospace Engineering
Delft University of Technology
Kluyverweg 1, 2629HS,Delft
The Netherlands
Email: A.Gangolirao@tudelft.nl

ABSTRACT

Over the last decades, aviation has become a dominant way of travelling for human beings. However, the global warming and ozone depletion have become the major problems for humankind. Although aviation only counts for a minority of total pollutions, it shouldn't be ignored any more. Therefore, the ACARE has set an ambitious objective for the year of 2050 to reduce CO_2 emission by 75%, NOx emission by 90% and noise emission by 65% compared to these levels in 2000 [1].This reduction is to be achieved by combined improvements in aircraft, propulsion systems and air traffic management systems.

To achieve the ACARE goal, a novel multi-fuel hybrid engine concept was proposed for a multi-fuel blended wing body aircraft. A parametric analysis has been carried out in previous work, and the reference point was initially chosen at cruise. This paper continues to analyse the cycle performance of the hybrid engine. Firstly, the impacts of using a mixer was analysed at the reference point; secondly, a comparison was made between the hybrid engine and a conventional engine; furthermore, the hybrid engine performance was analysed at various operating altitudes and Mach number; additionally, the impacts of the inter-stage turbine burner were investigated. Finally, the impacts of fuel ratio on the engine performance was examined for a given thrust at take-off.

NOMENCLATURE

ACARE	Advisory Council for Aeronautics Research in Europe
CTL	Coal To Liquid
FN	Net Thrust
GTL	Gas To Liquid
GSP	Gas turbine Simulation Program
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ITB	Inter-stage Turbine Buner
LHV	Low Heat Value
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
macha	Flight Mach number
mdot	air mass flow
SFC	Specific Fuel Consumption
SM	Surge Margin
UHC	Unburned Hydro Carbon
Z_p	Flight altitude

Subscript

1	lower pressure
2	high pressure
4	high pressure turbine inlet
46	low pressure turbine inlet
c	corrected value
in	inlet

*Corresponding author

INTRODUCTION

Since the first commercial aircraft flew, the demand for air transport has risen dramatically. In the past ten years, passenger numbers have grown by 45%. Freight traffic has increased by more than 80% on a tonne-kilometre basis [2]. Along with these positive developments, some serious challenges for the environment (emissions), the community (noise) and the availability of fuel resources are encountered by aviation [3]. The main pollutions from air traffic are combustion emissions and noise emission. As compared to 40 years ago, aircraft has been 20 decibels quieter and 70% more fuel-efficient, reducing carbon monoxide emissions by 50% and unburned hydrocarbon and smoke by 90% [2]. It is estimated that air traffic will grow by 5% annually in the future, and this will result in the growth of aviation related CO_2 emission by 2-3% per year [4].To summarize, air transport is highly responsible for environmental impact.

During past years, most efforts have been put to improve engine thermal efficiency and propulsive efficiency. Some so-called "green engines" have been investigated. The first candidate is the geared turbofan engine [3] which was designed for improving component efficiencies to reduce fuel burn and noise. One more concept named intercooled recuperated aero engine was proposed for the reduction of emissions and fuel consumption [5]. Apart from these two, open rotor concept [6] also has the potential to reduce fuel consumption. However, CO_2 emission is the product of chemical reactions between the carbon content of a fuel and air, as long as the conventional fuel is in use, the ACARE goal to reduce CO_2 emission becomes ambitious. To achieve this target, alternative fuels have been put forward.

It is anticipated that aviation will see a significant use of alternative fuels, starting with synthetic fuels such as GTL, CTL (with reduced C/H ratio) and biofuels, as can be observed in Figure 1. Certainly, in longer time, hydrogen or hydrogen rich fuels, such as LNG can be an option to reduce the carbon foot print of aviation. Therefore, a hybrid engine for multi-fuel blended wing body system was investigated [7].

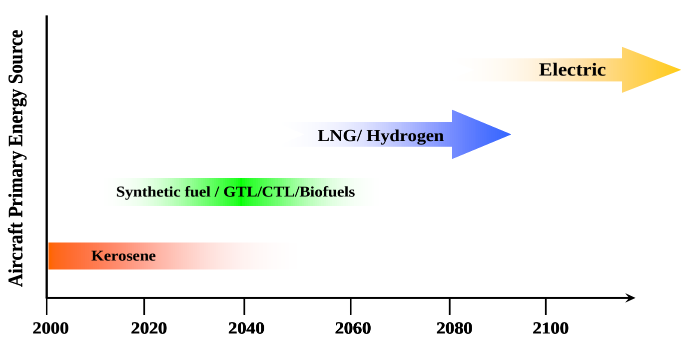

Figure 1: Anticipated energy trend for future long range aircraft [8].

To overcome the storage problems of alternative fuels in a conventional aircraft, a multi-fuel blended wing body aircraft concept is proposed and presented in Figure 2. Cryogenic fuels such as Liquid Hydrogen\Liquid Natural Gas (LNG) and kerosene are considered. Due to larger space available, the cryogenic fuel tanks can be located in the fuselage. Additionally, the free space in wings is still utilized for storing kerosene. In a conventional aero engine, it is not possible to consume different types of fuels in a single combustor, therefore, an engine concept is suggested with two combustion chambers in series for the two fuels: the hybrid engine.

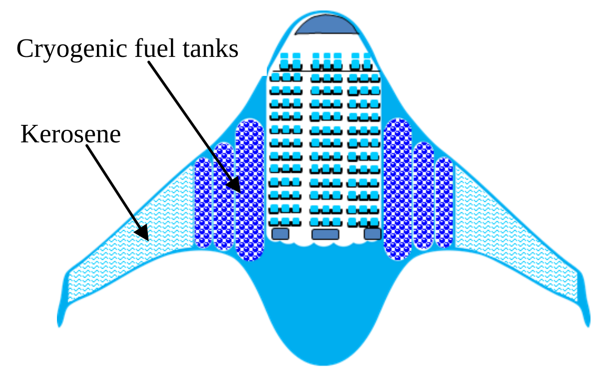

Figure 2: A multi-fuel blended wing body aircraft.

A PROPOSED HYBRID ENGINE ARCHITECTURE

The proposed hybrid engine configuration is shown in Figure 3. It is a combination of several novel technologies. The main features of this engine configuration are as below:

- Counter rotating fans which is good for boundary layer ingestion and improves the propulsive efficiency.
- Two combustion chambers, one is burning cryogenic fuels such as liquid hydrogen/liquid natural gas; the other one is an inter-stage turbine burner which is burning kerosene/biofuels [9,10].
- Since the flammability limit for hydrogen is much wider than for kerosene, the combustion can take place at lean conditions [11].
- Using liquid hydrogen in the first combustion chamber will increase the concentration of water vapour and reduce the concentration of O_2 in the second combustion chamber, thus creating a vitiated environment for Flameless Combustion [11].
- The use of flameless combustion technology in the second combustor will minimize the emission of CO, NOx, UHC and soot [11].
- Cryogenic fuel (hydrogen in this paper) is used as coolant to reduce the temperature of bleed cooling flow. The flow path is shown in Figure 4. Liquid hydrogen is chosen as the coolant in this case. It comes out from the fuel tank and exchanges heat with the bleed air from the compressor. After exchanging heat the temperature of bleed air is reduced and the amount of bleed air required to cool the turbine is decreased. Meanwhile, the temperature of hydrogen is increased which reduces the use of combustion heat to

increase its temperature, thus resulting in less fuel consumption for a given temperature within combustion chamber.
- The implementation of a mixer enables a slight increase of thrust, reduction of the SFC and the jet noise.

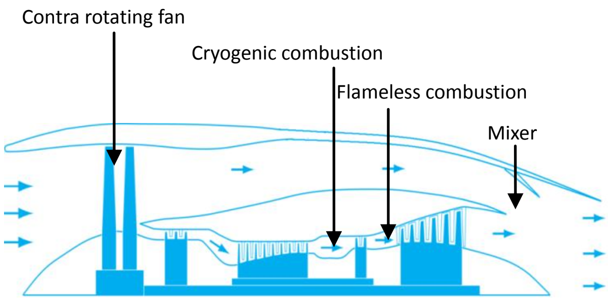

Figure 3: Schematic of a proposed hybrid engine concept.

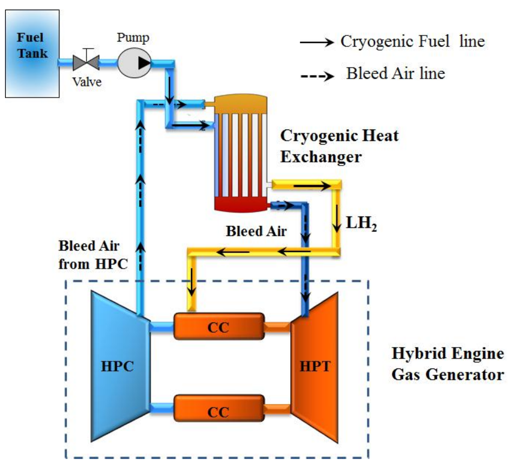

Figure 4: Schematic of the bleed cooling system.

CYCLE ANALYSIS PROCESS FOR A GAS TURBINE PRELIMINARY DESIGN

An aircraft propulsion system has to be able to meet different requirements at various operating points in a flight mission, therefore, designing an engine is never a single point performance analysis. For example, cruise is a point where most fuel is consumed, hence, it requires higher efficiency; take-off is the most mechanically critical point where the highest turbine inlet temperature is reached and the risk of damaging the engine has to be taken into account at this point; most engines are sized at top of climb where the components of an engine are highly aerodynamically loaded. Theoretically, the engine operating envelop should be wider than the aircraft operating envelop. On top of all the characteristics, the thermodynamic performance of an engine needs to be fully understood during the engine conceptual design phase. Consequently, an engine cycle analysis is highlighted.

Cycle analysis is a process of determining thermodynamic performance of an engine [12]. It can be further divided into design and off-design cycle analysis. Design cycle analysis determines the engine performance at the reference point(s). Traditionally, the reference point is a single point where an engine spends most time or a point where the high power is required, such as cruise or take off. However, a multi-points design concept has been discussed more and more. In multi-points design, several disciplinary are taken care simultaneously, including thermodynamic, aerodynamic, acoustic and et.[13]. By doing this, a better optimized engine is expected. A fixed geometry of an engine is delivered from the design cycle analysis.

Undoubtedly, an engine is never operated at one point or several points. Therefore, after comprehending the design cycle characteristics, an off-design cycle analysis is demanded. Off-design analysis evaluates the engine performance at operational operating conditions. Several elements are involved in the off-design performance, including ambient conditions, flight conditions, component maps, and the reference point(s) performance.

At the beginning of a novel engine design, not all the requirements for the engine are clear enough. Things are developed step by step, which makes it difficult to consider everything in the meantime. Therefore, a single point design method is used in the preliminary design phase. The hybrid engine presented in this paper is designed for a long range aircraft, for which cruise occupies most time. Hence, the cruise is determined as a reference point. Inevitably, the take-off becomes an off-design point. The operating conditions and corresponding thrust requirements at these two points are given in Table 1. The liquid hydrogen and kerosene were implemented for two combustion chambers respectively.

Table 1: Operating conditions and thrust requirements.

Engine Rating	Altitude [m]	Mach NO.	ΔTemp.	Thrust [kN]
Cruise (reference point)	12000	0.8	ISA	45
Take-Off	0	0.2	ISA	200

The specific fuel consumption used to analyse the performance of the hybrid engine is redefined in equation 1, where the hydrogen is normalized with respect to kerosene.

$$SFC = \frac{\dot{m}_{hydrogen} * LHV_{hydorgen} / LHV_{kerosene} + \dot{m}_{kerosene}}{FN} \tag{1}$$

DESIGN CYCLE ANALYSIS

The hybrid engine cycle parametric analysis has been carried out at the reference point using an in-house thermodynamic model in the previous work [7] . This paper continues discussing the effects of using a mixer for the hybrid engine.

It is known that using a mixer can enhance the performance of an engine slightly. Figure 5 presents the variation of the specific fuel consumption with the increase of the bypass ratio. The solid line indicates an unmixed hybrid engine, and the dash line represents a mixed hybrid engine, which also validates in Figure 6. It can be observed that the specific fuel consumption of the mixed engine is lower than the unmixed one until a crossing point is met, after which the advantages of using mixer disappears as increasing the bypass ratio.

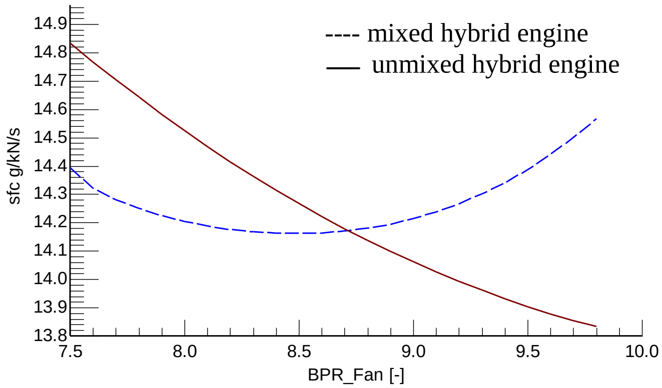

Figure 5: The variation of SFC with various bypass ratio for mixed and unmixed engine configuration.

Figure 6 shows the variation of net thrust with increase of the bypass ratio for a mixed and an unmixed hybrid engine concept. It demonstrates that the thrust decreases as bypass ratio increase. However, the thrust of the mixed configuration is higher than the unmixed one till the bypass ratio of about 8.7. Afterwards, the unmixed engine generates more thrust.

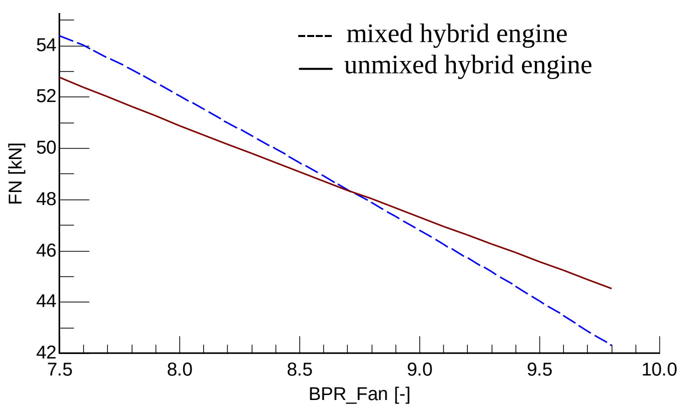

Figure 6: The variation of FN with various bypass ratio for mixed and unmixed engine configuration.

According to the results indicated in Figure 5-6, excessively high bypass ratio brings draw backs rather than advantages for a turbofan engine. In addition, in order to reduce the installation penalty and to enhance the benefits of using boundary layer ingestion, it is also better to keep the bypass ratio relatively low.

Taking all the factors mentioned above into account, the hybrid engine was optimized using the in-house model [7]. The optimized hybrid engine cycle is presented in Table 2.

Table 2: The hybrid engine design parameters and performance.

Engine Design Parameters	
Corrected mass flow [kg/s]	866.85
Bypass ratio	8.5
Fan pressure ratio	1.8
LPC pressure ratio	1.8
HPC pressure ratio	18.5
HPT inlet temperature [K]	1499.1
LPT inlet temperature [K]	1150
Engine Performance	
SFC [g/kN/s]	14.161
Net thrust [kN]	45.011
mdot, hydrogen [kg/s]	0.2105
mdot, kerosene [kg/s]	0.047

A MODEL OF THE HYBRID ENGINE FOR OFF-DESIGN CYCLE ANALYSIS

A 0-D thermodynamic model was created to analyze the performance of the hybrid engine. The Gas turbine Simulation Programme was chosen as a modelling tool. The GSP was developed by Dutch National Aerospace Laboratory and Delft University of Technology. The reason for choosing GSP was multi-fold. First of all, it is a component-based gas turbine modelling environment [14], which provides the flexibility to build various gas turbine models, especially for those having novel architectures like the hybrid engine. Secondly, GSP is a powerful tool for gas turbine performance prediction at both steady state and transient mode. Besides, the available components maps enables making off-design models easily. Furthermore, GSP is quite suitable for parametric analysis in the preliminary design phase of a gas turbine.

The schematic engine model is demonstrated in Figure 7, where the hybrid engine off-design performance is examined. The engine booster is integrated into the fan core. The component number 10 controls the bleed cooling fraction for the high pressure turbine. Additionally, the bleed cooling system presented in Figure 4 is not simulated in this model.

Some assumptions were made for the off-design analysis:

- Component efficiencies were constants;
- Bleed cooling fraction was constant;
- Combustion efficiencies and pressure losses were constants;
- Mechanical efficiencies were constants;
- Static pressure ratio of bypass and core was unity;
- Pressure loss during mixing process was constant;
- A one stage generic fan map was applied instead of a contra rotating fan map;
- Gas properties were averaged over the flow cross area at entry and exit stations only [14].

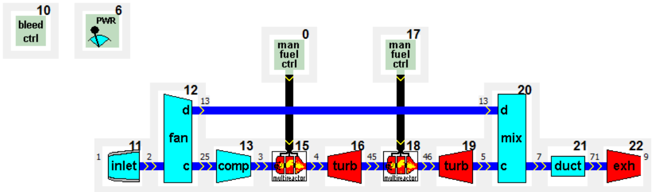

Figure 7: Schematic of the hybrid engine model.

In GSP, the Newton-Raphson solver was applied for iteration of the off-design calculation. A calculation iteration process is presented in Figure 8. The conservation of mass, momentum and energy are maintained during the whole process.

OFF-DESIGN CYCLE ANALYSIS

An engine is always operated at multi points within an operating envelope other than just at the reference point. Therefore, it is desirable to study the variation of engine performance at the diverse operating conditions. In this section, multiple flight altitudes, Mach number and thrust settings are incorporated into different cases as listed.

1) Comparison of engine performances with various thrust settings between the hybrid engine and a mixed conventional turbofan engine at take-off;
2) Variation of the specific fuel consumption and net thrust with flight conditions;
3) Comparison of engine performances at different inter-stage turbine burner exit temperatures within an engine operating envelope;
4) The ratio of fuel flows between hydrogen and kerosene was varied to investigate how the specific fuel consumption changed for a given thrust at take-off.

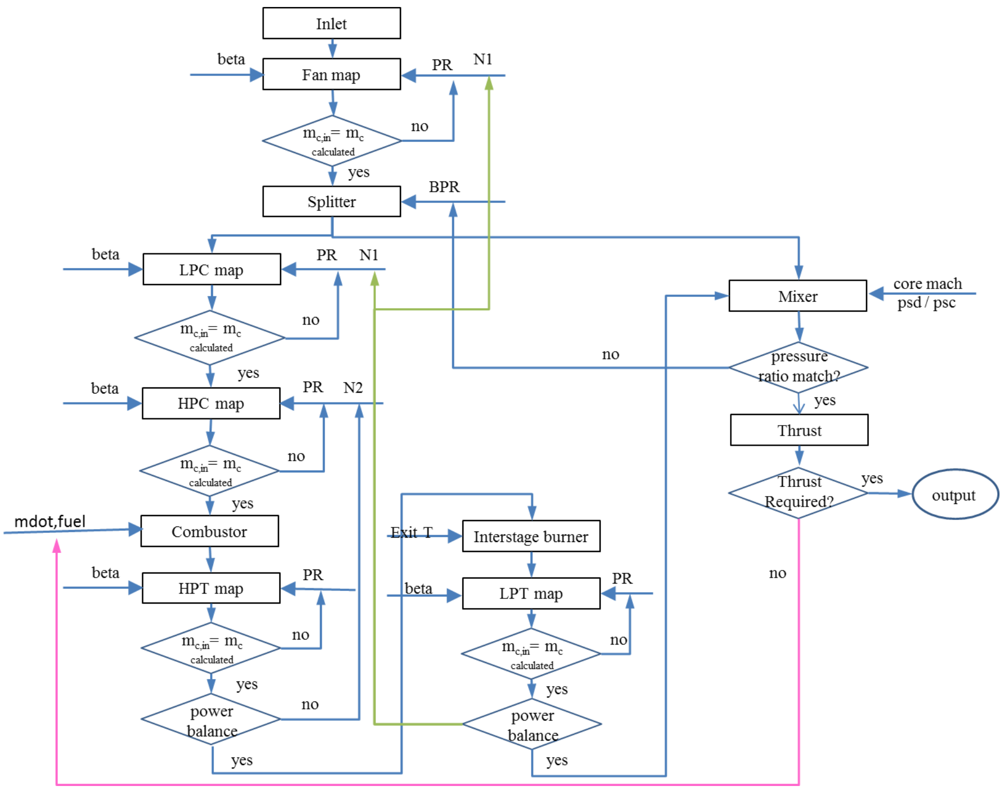

Figure 8: Iteration procedure of cycle analysis.

- **Comparison of engine performance with different thrust settings between the hybrid engine and a conventional mixed turbofan engine.**

One of the features for the hybrid engine is having an inter-stage turbine burner. Some research [9,10,15] have been done to investigate the effects of the ITB for separate-exhaust turbofan engines. However, for a mixed engine configuration, it was hardly considered. Therefore, this section concerns the off-design cycle analysis of a mixed hybrid engine concept at a steady state condition, namely take-off due to the fact that the highest burner exit temperature and spool speeds are encountered at take-off, which makes it a big challenge for the mechanical and cooling system design.

The performance of the hybrid engine is compared to a conventional mixed turbofan engine for various thrust settings at take-off. The same reference point and inputs were selected for the hybrid engine and the conventional engine. Additionally, the low pressure turbine inlet temperature is kept as constant intentionally for the hybrid engine.

Figure 9 presents the variation of the specific fuel consumption with respect to different thrust settings. It can be observed that the specific fuel consumption reduces as increasing thrusts for both engines. However, the variation of the SFC is more for the hybrid engine, which deteriorates the engine off-design performances. Moreover, the specific fuel consumption of the hybrid engine is also higher than the conventional engine due to the implementation of the ITB.

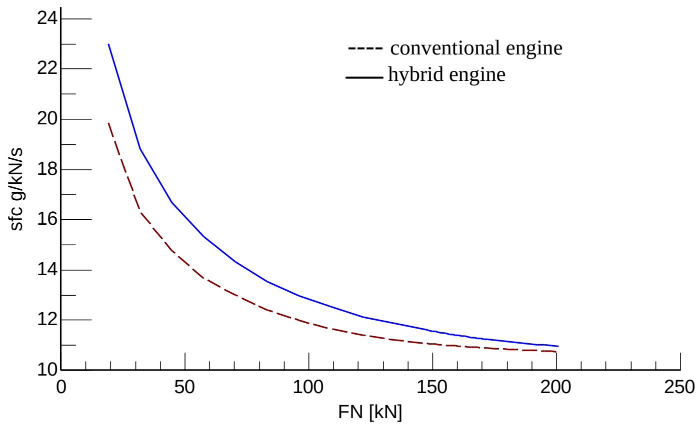

Figure 9: Variation of specific fuel consumption versus thrusts

Figure 10 indicates the variation of the total fuel consumption with various thrust settings. The total fuel consumption of the hybrid engine is defined in equation 2.

$$m_{dot,\,fuel} = \dot{m}_{hydrogen} + \dot{m}_{\mathrm{ker}osene} \qquad (2)$$

It can be observed that the total fuel consumption of the hybrid and conventional engine increase with increasing the thrust. However, the conventional engine consumes more fuel than the hybrid engine for a given thrust.

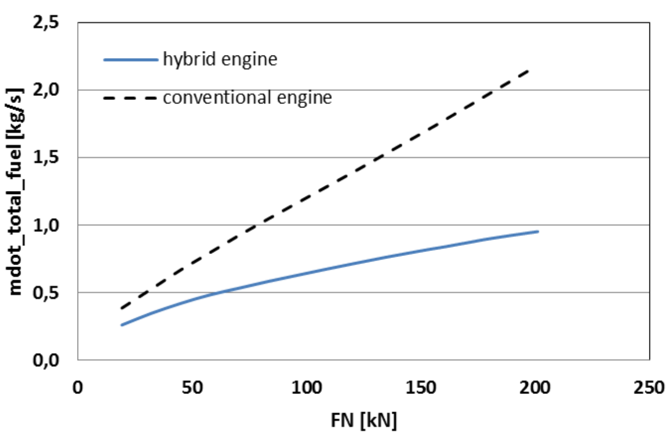

Figure 10: Variation of total fuel consumption versus thrusts.

Figure 11 demonstrates the variation of the HPT inlet temperature with thrust requirements. It indicates that the HPT inlet temperature increases with increasing the thrust requirements for both engines. Yet the hybrid engine has lower turbine inlet temperature than the conventional engine for a given thrust, which implies that the hybrid engine has the potential to reduce NO_x emission.

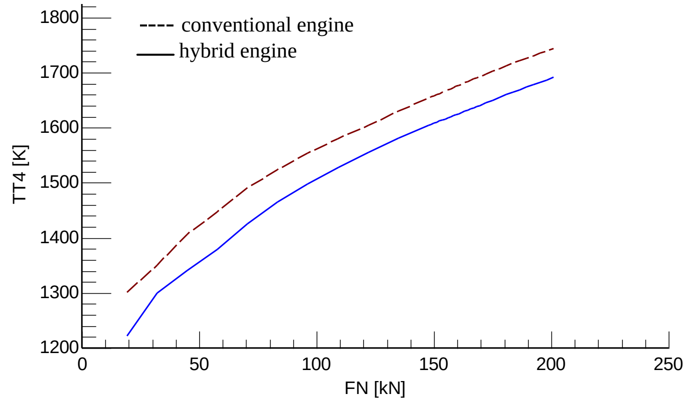

Figure 11: Variation of HPT inlet temperature versus thrusts.

Figure 12-13 demonstrate the variations of low and high pressure shaft speeds with different thrust settings. The solid line represents the hybrid engine, and the dash line represents a conventional engine. Figure 12 indicates that the low pressure shaft speed increases with increasing the thrust requirement for both engines. However, the shaft speeds of the hybrid engine is lower than the conventional engine for the same thrust. The same trend can be observed in Figure 13 for the high shaft speeds. Both Figure 12-13 provides the possibility that the rotating components life can be extended using ITB for a given thrust.

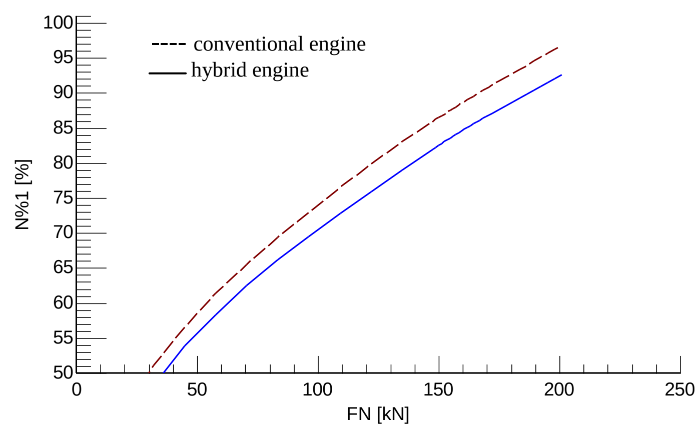

Figure 12: Variation of low pressure shaft speeds versus thrusts

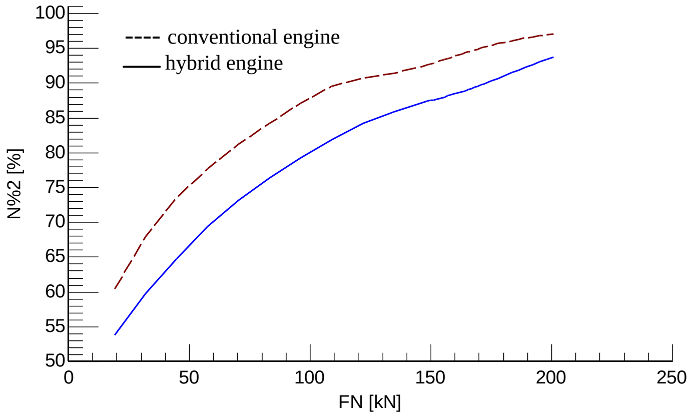

Figure 13: Variation of high pressure shaft speed versus thrusts.

➢ **Variation of the hybrid engine performance with various flight altitudes and Mach number.**

In this section, the LPT inlet temperature is still kept constant. The flight altitudes and Mach number are varied to analyse the engine performance.

Figure 14 presents the variation of SFC with flight Mach number for various flight altitudes. It indicates that for a given flight Mach number, the SFC decreases with increasing flight altitude, due to the reduction of the ambient temperature.

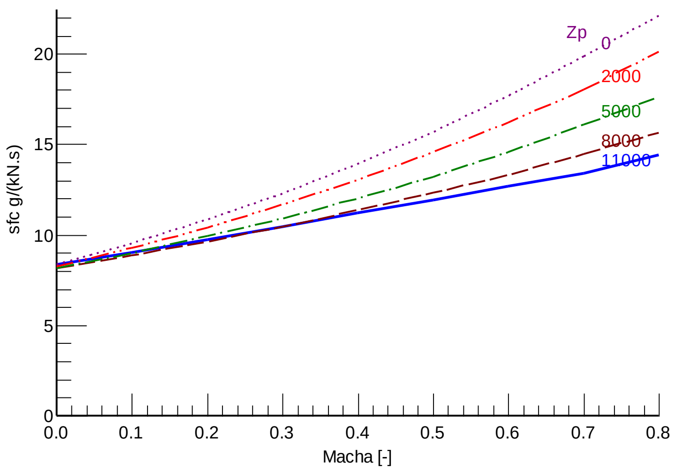

Figure 14: Variation of SFC with flight Mach number for various altitudes.

Figure 15 shows the variation of net thrust with the flight Mach number for various flight altitudes. It can be observed that for a given Mach number, thrust decreases with increase of flight altitude, due to the decrease of ambient temperature, and air density.

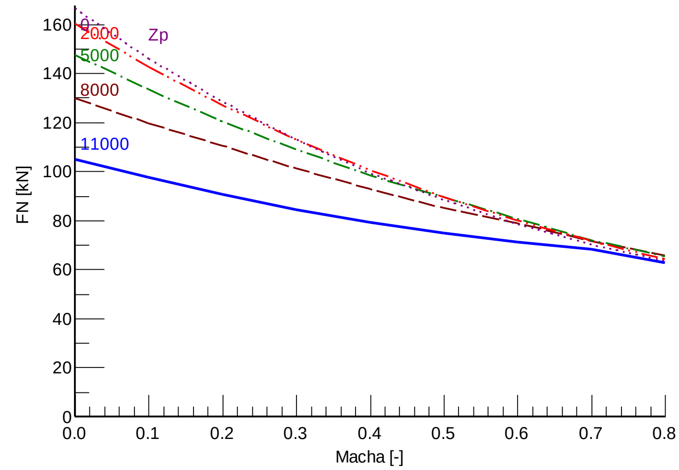

Figure 15: Variation of FN with flight Mach number for various altitudes.

➢ **Impact of the inter-stage turbine burners exit temperatures to the engine performances.**

The parametric cycle analysis of a turbofan engine with an inter-stage turbine burner has been carried out by Liew, K.H. et. al. [15]. In this section the behaviour of the hybrid engine during a climb process is simulated, by which the impacts of the ITB exit temperature is analysed. A flight envelop was created for the hybrid engine as shown in Figure 16, where the climb thrust requirements are scheduled. Accordingly, the temperature of the inter-stage turbine burner exit is varied.

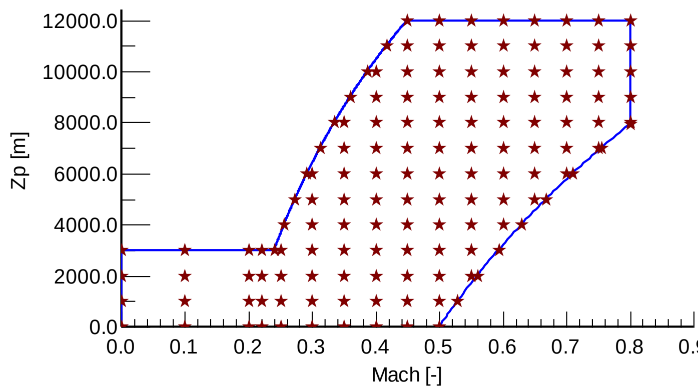

Figure 16: A flight envelop of the hybrid engine

Figure 17 presents the scheduled thrust variation with respect to various flight altitudes and the corresponding flight Mach numbers. The flight Mach number is not presented in this figure, which is also the same for Figure 18-21.

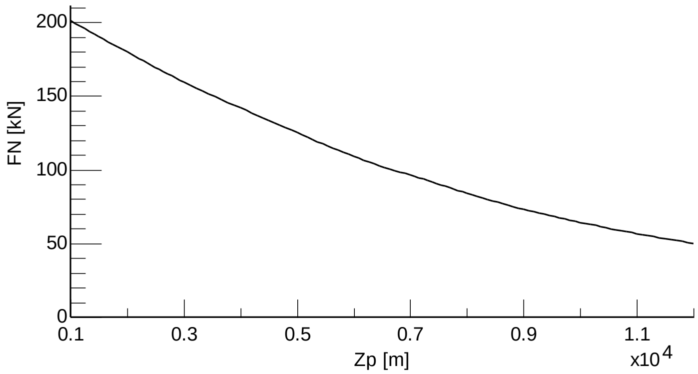

Figure 17: Variation of scheduled thrust with flight altitudes.

Figure 18 presents the variation of the specific fuel consumption at various operating points for different ITB exit temperature, where the solid line represents 1550K, and the dash line indicates 1350K. On one hand, it indicates that the specific fuel consumption increases with increasing the flight altitudes and Mach number for a given ITB exit temperature. On the other hand, increasing the ITB exit temperature leads to the higher specific fuel consumption.

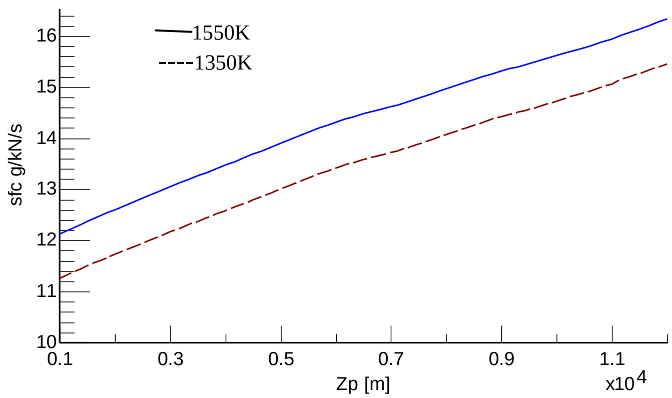

Figure 18: Variation of specific fuel consumption versus flight altitudes.

Figure 19 presents the variation of the high pressure shaft speeds at various operating points for different ITB exit temperature. Due to the reduction of thrust requirements, the shaft speed is reduced for different ITB exit temperature until 11000 meters where the tropopause is reached, above which the ambient temperature remains constant and the air density reduces further. It slightly speeds up the shaft speeds. However, for a given thrust at a specified operating point, the shaft speed is lower when the ITB exit temperature is increased, which is because of the lower pressure ratio of the high pressure compressor, as presented in Figure 20.

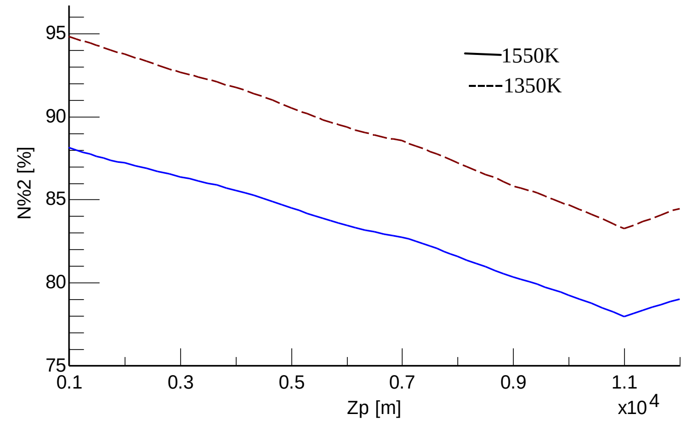

Figure 19: Variation of high pressure shaft speed versus flight altitudes.

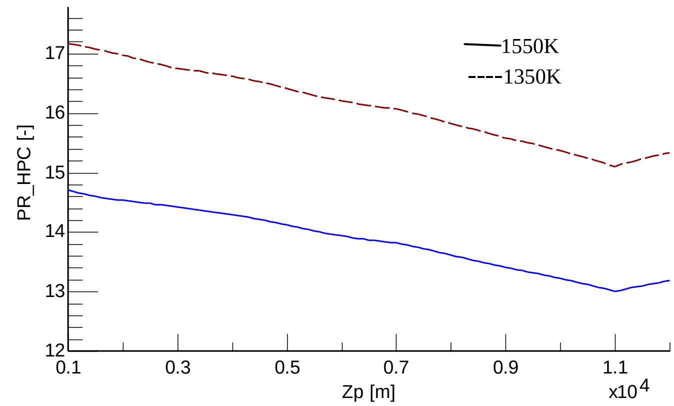

Figure 20: Variation of high pressure compressor pressure ratio with various flight altitudes.

Figure 21 presents the variation of the low pressure shaft speeds at various operating points for different inter-stage turbine burner exit temperatures. Unlike the behavior of the high pressure shaft speeds, the low pressure shaft speeds doesn't vary too much. Above 11000 meters, the similar trend can be observed, which is caused by the same reason. Besides the low pressure shaft speeds decreases as increasing of the ITB exit temperature.

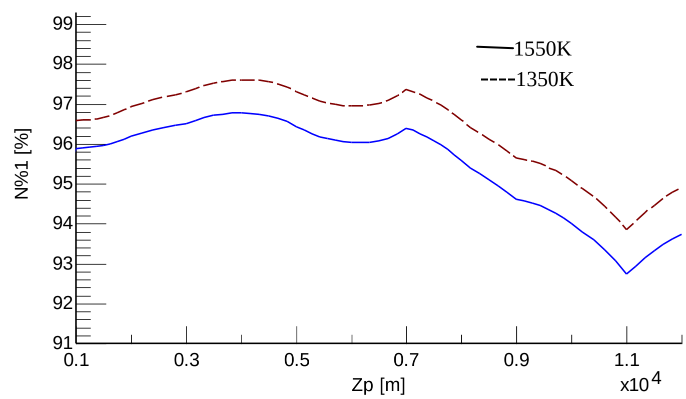

Figure 21: Variation of low pressure shaft speed versus flight altitudes.

Figure 22-23 present the variation of the surge margin in the core and bypass of the fan. Figure 22 indicates that the core surge margin of the fan reduces with the increase of the flight altitudes for a given LPT inlet temperature. Moreover, increasing the LTP inlet temperature decreases the surge margin.

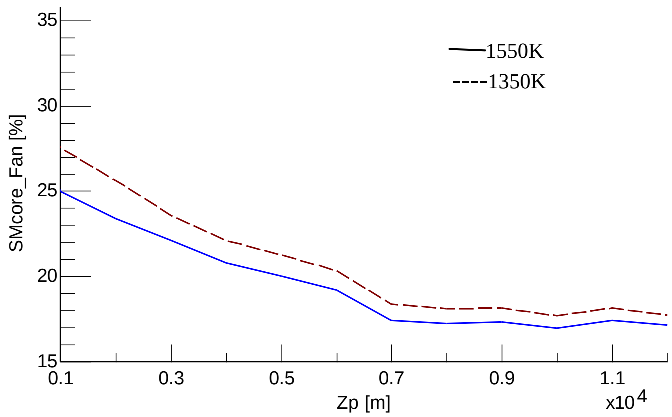

Figure 22: Variation of the surge margin of core fan with flight altitudes.

Figure 23 shows that the bypass surge margin of the fan reduces with the increase of the flight altitudes for a given LPT inlet temperature. In addition, the surge margin reduces when the LPT inlet temperature increases.

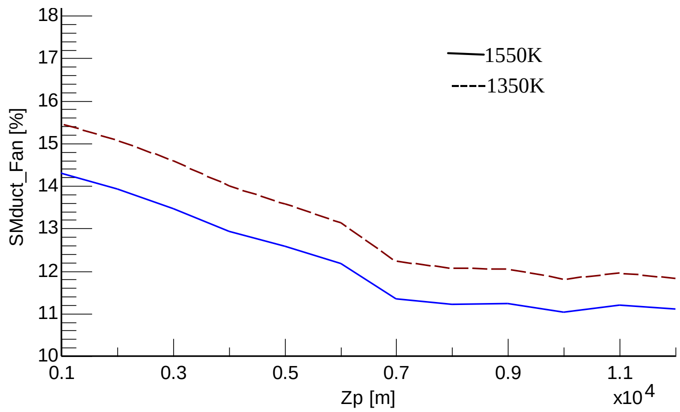

Figure 23: Variation of the surge margin of duct fan with flight altitudes.

➢ **The variation of fuel consumption with different fuel ratios for a given thrust at take-off**

Unlike a conventional engine, the hybrid engine burns two types of fuels. Due to lower volume density, larger space is desired to store cryogenic fuels, for instance, the liquid hydrogen and liquid natural gas, which makes it a big challenge for an aircraft. Therefore, it is vital to optimize the storage space. To analyze the influence of various combinations of fuels, a terminology named the fuel ratio is defined in equation 3.

$$R_{fuel} = \frac{\dot{m}_{hydrogen}}{\dot{m}_{kerosene}} \qquad (3)$$

Figure 24 presents the variation of SFC with fuel ratios for a given thrust at take-off. It shows that the specific fuel consumption reduces with increasing the fuel ratio. Because the fuel ratio is increased by increasing the mass flow of the hydrogen or decreasing the mass flow of kerosene, both will inevitably lead to the increase of the high pressure turbine inlet temperature or reduction of low pressure turbine inlet temperature, which improves the engine efficiency, thus reducing the specific fuel consumption.

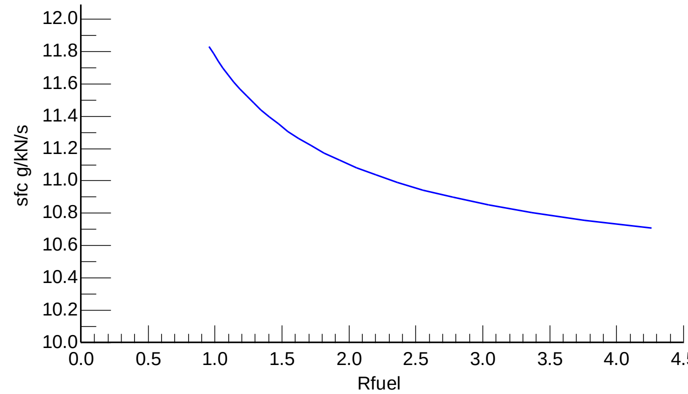

Figure 24: Variation of SFC with the fuel ratio for a given thrust.

However, increasing the mass flow rate of the hydrogen requires more storage space, making it a challenge for aircraft. In the blended wing body aircraft as presented in Figure 2, larger space is available than a conventional aircraft. Therefore, if the aircraft is optimized suitably, it is highly possible to carry enough cryogenic fuels.

CONCLUSIONS

The engine performance changes with various operating conditions. This paper analyzed the variation of engine performance at various ambient conditions and thrust settings. The simulation results showed that:

- The implementation of a mixer in a turbofan engine can slightly reduce SFC and increase FN. However, the benefits of using mixer decrease as increasing the bypass ratio;
- Increasing the thrust settings leads to the increase of shaft speeds and the high pressure turbine inlet temperatures for both hybrid and conventional engines. However, the shaft speed and turbine inlet temperature of the hybrid engine are relatively lower than the conventional engine for a given thrust, which provides the possibility to extend the lifespan of the rotating components and to reduce the NO_x emission;
- For a given thrust schedule, increasing the inter-stage turbine burner exit temperature leads to the increase of

the specific fuel consumption and the reduction of shaft speeds and the fan surge margin;

- Increasing the ratio of the hydrogen to kerosene can enhance the engine efficiency, but the capacity of an aircraft for storing fuels has to be taken into account.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 284636. The authors would like to acknowledge the support of all the partners of this project.

REFERENCES

1.Advisory Council for Aeronautics Research in Europe(ACARE), "Flight path 2050 Europe's vision for aviation", Report of the High Level Group on Aviation Research, Publication Office of European Union, ISBN 97892 79197246, 2011.

2. Air transport action group (ATAG), "The economic & social benefits of air transport", 2005.

3.Riegler, C. and Bichlmaier, C., "The geared turbofan technology opportunities, challenges and readiness status", Germany.

4. Air transport action group (ATAG), "The economic and social benefits of air transport 2008", 2008.

5. Boggia, S. and Rud, K., "Intercooled recuperated gas turbine engine concept", 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, Arizona, July 2005.

6. Uwe Fuss and Parry, A.B., "SAGE1 Demonstrator: enabling open rotor technologies", ISABE-2011-1305.

7. YIN, F., and Rao,A.G., "Performance of multi-fuel hybrid engine for blended wing body", proceedings of 4th international symposium on jet propulsion and power engineering, Xi'an, China, 2012.

8. Rao, A. G., and van Buijtenen, J.P., "Basic Concepts: Propulsion and Power", Encyclopedia of Aerospace Engineering, Eds:- Richard Blockley & Wei Shyy. Wiley, 2010.

9.Liu, F., and Sirignano, W.A., "Turbojet and turbofan engine performance increase through turbine burners", 38th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, AIAA-2000-0741.

10.Sirignano, W.A, and Liu, F., "Performance increase for in gas-turbine engines through combustion inside the turbine", Journal of Propulsion and Power, Vol. 15(1), pp. 111-118, 1999.

11.Rao, A.G., Yin, F., and van Buijtenen, J.P., "A novel engine concept for aircraft propulsion", ISABE, Gothenburg, ISABE-2011-1341.

12. Mattingly, J.D., "Elements of gas turbine performance", McGraw-Hill Inc, 1996.

13. Schutte, J.S., "Cycle design exploration using multi-design point approach", a PhD thesis, Georgia Institute of Technology, 2009.

14. GSP Development Team, "GSP 11 User Manual - Version 11.1.0", National Aerospace Laboratory NLR, 2010.

15. Liew, K.H., Urip, E., and Yang, S.L., "Parametric cycle analysis of a turbofan engine with an inter-stage turbine burner", Journal of propulsion and power, Vol. 21, No.3, 2005.

