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A NOVEL HYBRID ENGINE CONCEPT FOR AIRCRAFT PROPULSION

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Abstract

The Advisory Council for Aeronautics Research in Europe (ACARE) has set ambitious objectives for civil aviation for 2020 and beyond; the major being reduction of CO_2 emission by more than 50%, for which significant improvements in the aircraft, propulsion and operational systems are required. However, at this moment it appears that this goal can not be achieved with evolutionary technology because most of the conventional technologies have already been exploited to their maximum and a technological plateau has been reached.

The paper presents a novel hybrid engine architecture for future aircraft, namely the Blended Wing Body (BWB). The proposed hybrid engine has a host of features including a hybrid combustion system consisting of two combustion chambers, which offers the possibility of operating on hydrocarbon fuels as well as liquid hydrogen / low carbon based fuels. Thus enabling the aimed reduction of CO_2 emissions without encountering the storage problems related to a pure hydrogen powered aircraft.

Nomenclature

Roman Symbols

F	thrust [N]
F_{SP}	specific thrust [N-s/kg]
P_0	total pressure [Pa]
Q	fuel heating value [MJ]
SFC	specific fuel consumption [g/kN-s]
T_0	total temperature [K]

Greek Symbols

π	ratio of total pressures [-]

Subscripts

0	total conditions
3	compressor exit/combustor entry
4	main combustor exit
45	HPT exit
46	ITB exit
5	LPT exit
7	nozzle entry conditions
9	nozzle exit conditions

Abbreviations

ACARE	Advisory Council for Aeronautics Research in Europe
BLI	Boundary Later Ingestion
BPR	Bypass Ratio
BWB	Blended Wing Body
CRF	Counter Rotating Fan
CTL	Coal to Liquid
GSP	Gasturbine Simulation Program
GTF	Geared Turbofan
GTL	Gas to Liquid
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ITB	Inter Turbine Burner
ITFC	Inter Turbine Flameless Combustor
LH2	Liquid Hydrogen
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
NGV	Nozzle Guide Vanes
NO_X	Nitrogen Oxides
OPR	Overall Pressure Ratio
TET	Turbine Entry temperature

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INTRODUCTION

Aviation is a great contributor to society, bringing people and cultures together and creating economic development across the globe. Air routes are the highways of the global economy [1]. The temporary halt of aviation activities within Europe caused by the volcanic eruptions in Iceland highlighted the deep impact which aviation has on the economy of developed countries. Whereas aviation is vital for the development of economy, there are specific challenges that have to be overcome in order to sustain the future growth of aviation.

With global warming and ozone depletion becoming one of the major problems faced by humankind and with ever-increasing air traffic, emissions from aircraft can no longer be ignored. Hence, there is an urgent need to reduce the emissions of CO_2, NOx, CO and other pollutants. The CO_2 emission from aircraft also contributes to the global warming [1]. The NOx predominates both in the vicinity of the airport and also during the cruise [2]. For a long flight, the NOx form a large fraction of the total emissions [3]. The emission norms will become more stringent in the coming years, with the consequent need to reduce pollutants level drastically [4]. The anticipated reduction at various fronts (noise, air pollution and fuel consumption) required to meet the future challenges, as envisioned by the ACARE are shown in Fig.1. It can be seen that reduction in CO_2, noise and NOx emission are the most prominent. It is targeted that CO_2 emission has to be reduced by 50% and NOx emission by 80% (the baseline was year 2000) [5]. This is to be achieved by a combined improvement in the aircraft, powerplant and the air traffic management system.

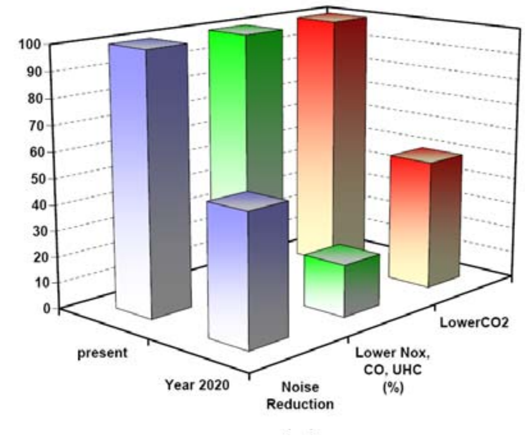


Fig. 1. ACARE vision for Europe

In order to meet these stringent demands, innovation is required on all fronts. Innovation in aircraft calls for new aircraft types. The blended wing body configuration seems to be the most promising concept for replacing the current cylindrical centre body fuselage aircraft, which has not changed much since the birth of commercial civil aviation. The blended wing body has been investigated by many research groups in the world and seems to be the next logical revolution in aircraft configuration. Some of the BWB aircraft concepts are shown in Fig. 2 & 3 below [6, 7].

Fig. 2. The silent aircraft initiative [6]

Fig. 3. The CleanEra Aircraft Initiative [7]

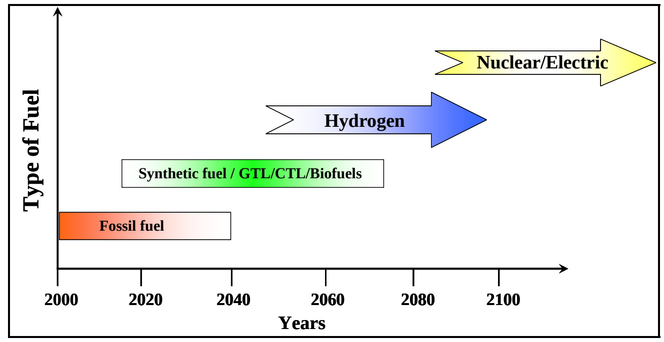


Fig.4. Anticipated trend in fuels for aviation [8]

MOTIVATION

Over the years gas turbine engines have improved significantly from the early pure jets to the current high bypass turbofan engines. The aspiration to make these engines stronger, lighter and more efficient has kept scientists and engineers occupied for decades, and continue to this day. Traditional ways of increasing engine efficiency include increasing the BPR, OPR and turbine inlet temperature [8]. These are fundamentally solid ways to improve turbofan engines, but all possess adverse effects which are becoming increasingly significant. Increasing BPR leads to increase in the engine weight and engine diameter, thereby increasing the drag and reducing the ground clearance. Increasing OPR leads to heavy and long engines. Turbine entry temperature is mainly limited by material technology level.

The GTF is a step change in the conventional engine architecture and will reduce the SFC significantly. However in the distant future, new engine architectures have to be envisioned which will be able to meet the stringent demands imposed on aviation. One of the main considerations in this regard is the availability of fossil fuels. With the dwindling resources of fossil fuels, it is anticipated that aviation will see a significant use of non conventional fuels, starting with synthetic fuels such as Gas to Liquid (GTL), Coal to Liquid (CTL) and biofuels. However if we want to reduce the carbon foot print of aviation, then we have to switch to hydrogen or hydrogen rich fuels. The anticipated trend of energy sources in aviation is shown in Fig. 4.

The energy density of hydrogen is higher than kerosene, thus allowing much less fuel to be taken onboard. However, the volume required by hydrogen is much higher than kerosene. Using hydrogen for aviation also has several environmental benefits [9]. Storing hydrogen in the liquid form is challenging and hence calls for innovative storage technologies. In a conventional aircraft, fuel is stored in the wings; however LH2 can not be stored in the wings because it has to be stored in pressurized cylinders and the wings of a conventional passenger aircraft are too thin to accommodate cylindrical tanks.

The Cryoplane concept that was investigated under the 5th Framework Program of the European Commission showed the advantages of using hydrogen for aviation [10, 11]. The environmental benefits of using hydrogen was highlighted and substantiated in this project. However the main problem was storing the cylindrical LH2 fuel tanks within the aircraft. The LH2 storage scheme envisaged in the Cryoplane project is shown below in Fig. 5. However this configuration is not so suitable from a passenger comfort, safety and aircraft aerodynamic efficiency point of view.

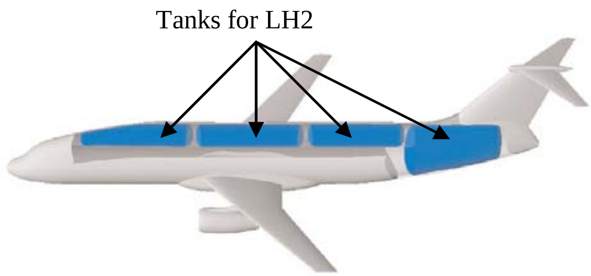


Fig.5. LH2 tanks storage scheme of "Cryoplane" project [10]

However, for future aircraft configurations, such as the BWB aircraft, the storage of LH_2 becomes manageable as the layout of such airplanes is more suited to accommodate large cylindrical fuel tanks outside the passenger area, as depicted in Fig. 6.

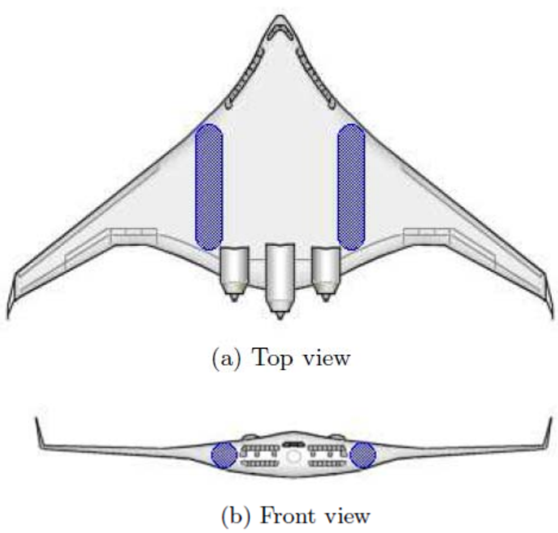


Fig. 6. A possible BWB layout with LH_2 tanks.

Further away from the centerline where wing thickness is reduced, liquid fuels (kerosene or biofuel) can be stored. Thus, a combination of Biofuel or synthetic fuel and LH2 seems to be a viable energy source for future aircraft configurations. This multi-fuel energy concept opens a whole new range of possibilities. The carbon emission from such configurations will be substantially less as compared to a conventional aircraft because of the increased aerodynamic efficiency and the use of hydrogen.

FUTURE ENGINE REQUIREMENTS

Even though the BWB aircraft concept is very promising, it alone cannot meet future challenges without drastic improvements in the propulsion system. Over the last 70 years, jet engine efficiency has improved significantly. This improvement has primarily been due to the increase in the bypass ratio (BPR) and the increase in the core thermal efficiency [12]. However this trend of increasing the BPR can not be sustained as is exhibited by the GP7000 engine designed for the A380 where the BPR was reduced in order to meet the noise emission [13].

The requirements from an engine for futuristic aircraft (like the BWB aircraft discussed in the previous section) are envisioned as follows;

- *Low Emissions*: The targeted reductions in CO2, NOx & CO by ACARE in the future have already been shown in Fig. 2. Reductions in soot emissions are also considered since they affect contrail cirrus properties.
- *Low Noise*: It is targeted that the cumulative noise from engine and airframe should be reduced by 50%, as shown in Fig.2.
- *Lower Installation Penalty*: The current trend in the gas turbine engines is to increase the engine BPR, which makes them bigger and larger. Even though the SFC of such engines is lower, the resulting aerodynamic drag and weight is higher, thus increasing their installation penalty.
- *Boundary Layer Ingestion (BLI)*: Future BWB aircraft configurations would have different requirements for the engines in terms of the aircraft-engine integration [14, 15]. The potential advantages of BLI are
    - Reduces the aerodynamic drag of the aircraft.
    - Increases the propulsive efficiency of the engines.
    - Enables embedded engine installation which can reduce the noise significantly.

THE HYBRID ENGINE

In order to exploit the unique opportunities provided by the above described multi-fuel BWB aircraft, a new engine configuration called as the "hybrid engine" has been conceived to meet the stringent demands put forth by the future aircraft, especially in terms of new aircraft architecture and aircraft engine integration challenges. The schematic of the engine is showed in Fig. 7. The main features of the new engine architecture are as follows;

- Counter rotating shrouded fans
- Two combustion chambers allow multiple types of fuel (to alleviate the storage problem related to pure LH_2 powered aircraft)
- Main combustion chamber on LH_2
- Inter turbine flameless combustor (ITFC) on liquid biofuel / kerosene fuel
- Bleed cooling by LH_2
- Higher specific thrust
- Low installation penalty, especially for BLI configurations as compared to high BPR engines

As can be seen, the novel engine proposed here has many new elements to it.

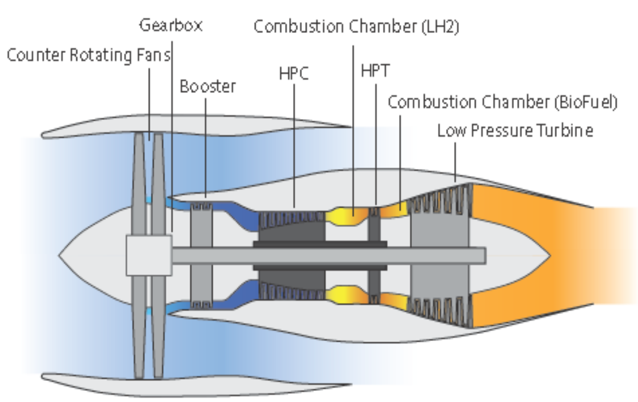


Fig. 7. Proposed Engine Layout

Counter rotating fan: As already mentioned the aircraft-engine integration of future BWB aircraft present unique challenges and require that the engine is buried within the nacelle and the engines are callable of ingesting the boundary layer. Such configurations also require that engines be smaller in diameter to reduce the nacelle wetted area. Thus it can be seen that the current trend of increasing bypass ratio and diameter of engines is not going to meet the requirements of future BWB class of aircraft. Studies have also shown that rear, embedded engines are favored for their potential noise reduction and compatibility with the airframe [14]. However ultra high bypass turbofans are not compatible for this.

The proposed hybrid engine with counter rotating fans will have a smaller diameter and higher propulsive efficiency for the same bypass ratio. Also since each stage of the fan is less loaded as compared to single stage fan architecture, a CRF can sustain more non uniformities in the flow generated due to BLI as compared to a conventional architecture. The EU sponsored project VITAL looked into CRF concept (shown in Fig.8) and it was concluded that this fan concept is a great leap by offering the same performance as a conventional fan(it manages the same airflow), but with lower tip speeds, thereby reducing fan noise [16].

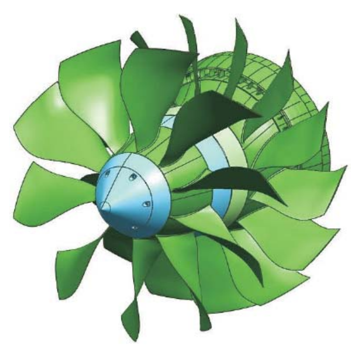


Fig. 8. The contra-rotating fan [16]

Dual Combustion System: The hybrid engine uses two combustion chambers as shown in Fig. 7. The main combustor operates on LH2 while the second combustor (between HPT and LPT) uses biofuel or synthetic fuel in the flameless combustion mode. Such a novel combustion system has never been used before for aero engines. The advantages of this unique design are as follows

- Since the flammability limit for H2 is much wider than for kerosene, the combustion can take place at lean conditions.

- The LH2 used for the first combustor can be used for cooling the bleed air (used for cooling the turbine vanes and blades).
- Using LH2 in the first combustion chamber will increase the concentration of water vapour and reduce the concentration of O2 in the second combustion chamber, thus creating a vitiated environment in which Flameless Combustion can be sustained using biofuel / synthetic fuel like GTL/CTL or any other liquid fuel.
- The use of flameless combustion technology for the second combustor will reduce the emission of CO, NOx, UHC and soot to a minimum.
- The reduced emission of soot and UHC will reduce the amount of nucleation centers available for condensation of the H2O in the plume, thus reducing the contrail formation.
- The second combustion chamber will not increase the length of the engine because it will utilize the inter turbine duct between HPT and LPT.
- Since the amount of fuel burnt in the first combustion chamber is more than the second, more LH2 is carried on board, thus optimizing the aircraft fuel carrying capacity.

Bleed Cooling: With increasing pressure ratio, the temperature of bleed air (the air that is used for cooling the hot section components like the HPT blades and vanes) also increases, thus increasing the amount of bleed airflow required to cool the hot components. This increase in the bleed airflow has an adverse effect on the efficiency.

The proposed hybrid engine uses both LH2 and biofuels. The liquid hydrogen (LH2) used in the main combustion chamber is an excellent heat sink and can be used for cooling the bleed air prior to burning in the combustion chamber, thus reducing the amount of bleed air required substantially. Also by using this novel technique, the amount of heat released by the hydrogen in the combustion chamber increases slightly, therefore reducing the fuel requirement even further. Studies have shown that using this novel technique can increase the overall efficiency of the engine significantly [17].

HYBRID ENGINE SETUP

Recent researches on the subject of ITBs include Liew et al [18], Liu and Sirignano [19], Sirignano and Liu [20], Chen et al [21]. Sirignano and Liu focused their research on combustion in the turbine itself to create a continuous combustion process, while Liew et al performed a parametric study of a distinct interstage turbine burner in the transition duct between the HPT and LPT.

To analyze the behavior of the hybrid engine, a thermodynamic model has been made as elaborated by Koon et al [22]. The model was validated for existing engines and with GSP® [23]. The engine analyzed is based on the GE90-94B engine. The ITFC is added between the HPT and LPT. The low pressure spool consists of the fan, booster and LPT. The high pressure spool links the HPT and HPC. The layout and numbering is shown in Fig. 9.

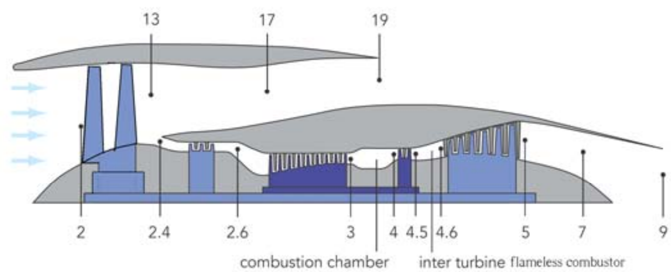
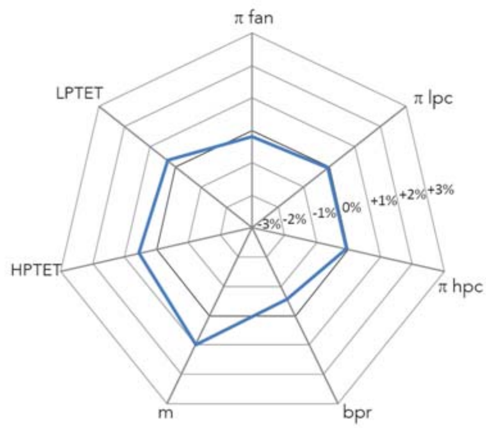
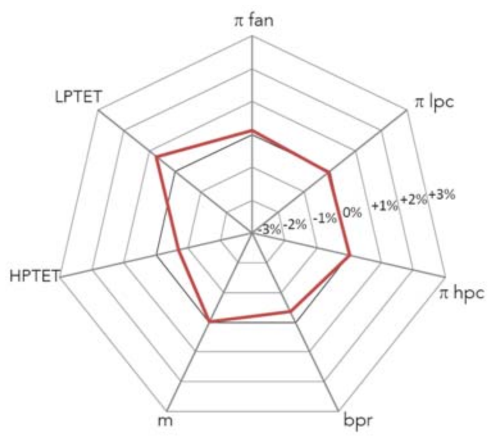


Fig. 9. Engine Layout and Numbering [22]

The thermodynamic model described in [22] is used to analyze the sensitivity of the hybrid engine to various design parameters. Fig. 10 a & b shows the effect of various design parameters on the specific thrust and SFC respectively. The diagrams consist of two parts: the legs, pointing outward from the center, and the web. On each leg, the change in response to a 1% increase of the parameter is indicated.



(a) Specific Thrust



(b) Specific Fuel Consumption

Fig. 10. Sensitivity analysis of various design parameters on hybrid engine (a) Specific thrust (b) SFC

RESULTS

In order to assess the feasibility of the hybrid engine concept, the design parameters are varied in order to understand the important parameters affecting the engine performance. The hybrid engine cycle for four different OPR is shown in Fig. 11. It is clear that because of the ITFC, the fuel flow and thermal efficiency of the hybrid engine differs from the conventional engine. The addition of heat within the ITFC at lower pressure impacts the thermal efficiency of the engine.

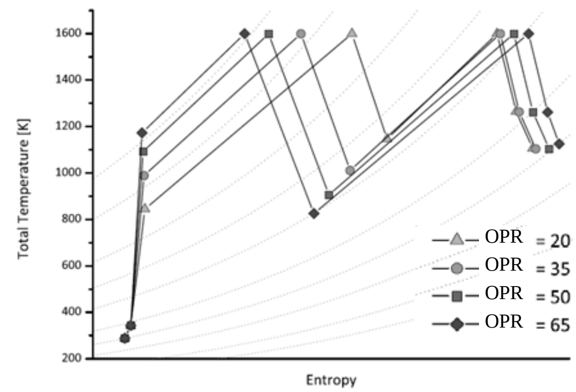


Fig. 11. T-S Diagram for different OPR

The effect of FPR and TET on the hybrid engine characteristics is shown in Fig. 12 (a) & (b) respectively. It can be seen that increasing the TET is better for the engine performance, which is also the case for conventional turbofan engines. However with respect to FPR, it can be seen that the optimum FPR increases with increase in TET

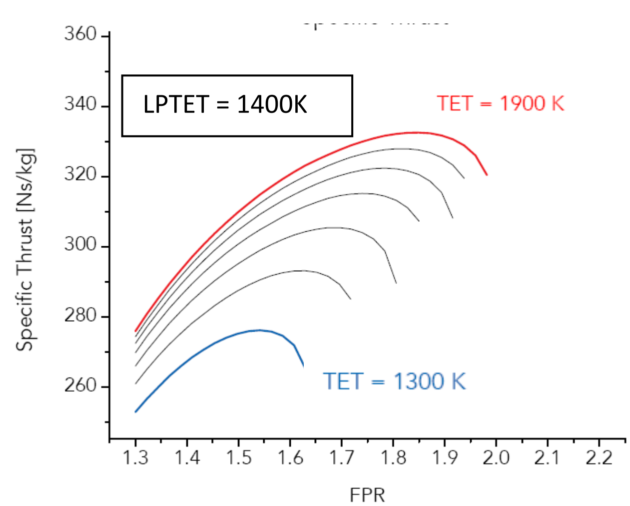


Fig. 12 (a)

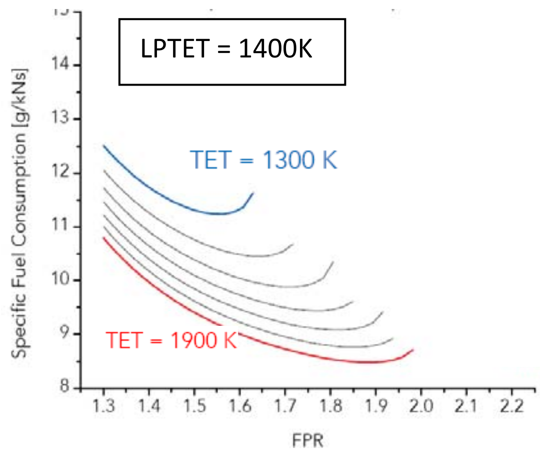


Fig. 12 (b)

Fig. 12. Effect of FPR and T04 on hybrid engine (a) Specific Thrust and (b) SFC

Mixed Configuration

The SFC of the proposed hybrid engine in an unmixed configuration is higher as compared to the baseline engine due to the use of reheat in the second combustion chamber. However the penalty in SFC is reduced substantially for a mixed configuration. This is due to the fact that energy from the high temperature core flow is transferred to the cold bypass flow in the mixer. The Fig. 13 shows the SFC for various engine configurations.

Number	Configuration
C1	Unmixed Hybrid Engine
C2	Mixed Hybrid Engine
C3	Unmixed Hybrid Engine with Bleed Cooling
C4	Mixed Hybrid Engine with Bleed Cooling
C5	Reference Engine (GE90-94B)

Table-1. various engine configurations

It can be seen that in the mixed configuration, the hybrid engine efficiency is better than the reference engine. Apart from increasing the efficiency, the mixer is beneficial for being used in an embedded configuration which is also beneficial from BLI and noise attenuation point of view.

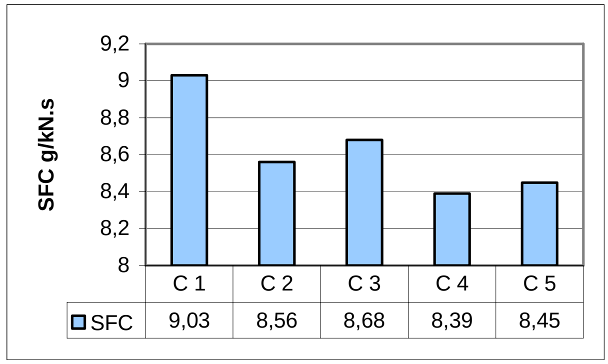


Fig. 13. SFC comparison for various engine configurations at take-off

The specific thrust comparison of various engine configurations is shown in Fig. 14. It is clear that all configurations of the hybrid engine have much higher specific thrust than the baseline engine. Thus for producing the same thrust, a much smaller engine is required. This is beneficial for reducing the installation penalty of the engine. Also, the engine diameter would be much smaller, enabling the hybrid engine to be used in BLI.

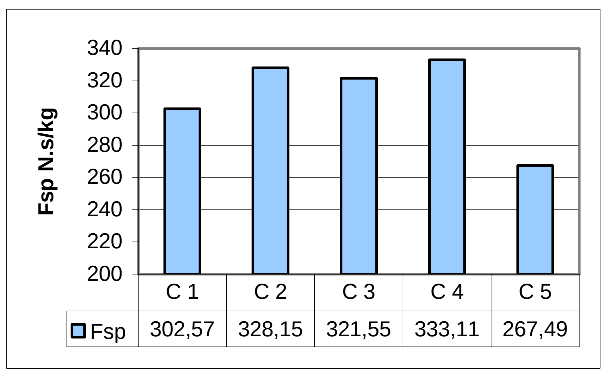


Fig. 14. Specific thrust comparison for various engine configurations at take-off

Since the hybrid engine uses LH2 and kerosene, the CO2 emission front the engine is reduced significantly. The Fig. 15 shows the carbon emission from various engine configurations and it can be seen that the proposed hybrid engine reduces the emissions drastically, by around 75%.

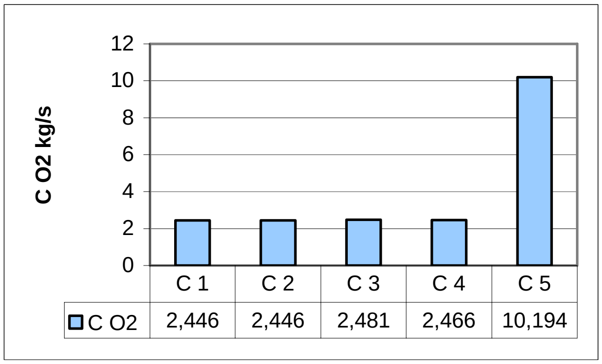


Fig. 15. Reduction in CO2 emission for various engine configurations at take-off

CONCLUSIONS

If civil aviation has to maintain its growth, radical changes in the aircraft and propulsion systems are required. The open-rotor concept offers an interesting option by increasing the propulsive efficiency. However blade containment and noise are two fundamental problems which seem to hinder the application of this technology to future aircraft concepts.

The paper presents a radically different propulsion concept that promises to reduce the carbon foot print of aviation. The hybrid engine has been conceptualized with respect to catering the needs of future aircraft configurations like the BWB aircraft.

In order to assess the feasibility of the hybrid engine concept, the design point performance is compared with the baseline engine, GE90-94B. When compared with the baseline engine, the SFC for the hybrid engine is around 0.8 % less and the CO2 emission is reduced by 75 %. The specific thrust of the hybrid engine is around 24% more than the baseline engine, thus reducing the engine diameter and associated drag & installation penalty of the engine. From the preliminary analysis, it is found that the proposed Hybrid Engine concept is very promising concept if the carbon foot print of aviation is to be reduced in the future.

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