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Performance Assessment of a Multi-Fuel Hybrid Engine for Future Aircraft

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ABSTRACT

This paper presents performance assessment of the proposed hybrid engine concept using Liquid Natural Gas (LNG) and kerosene. The multi-fuel hybrid engine is a new engine concept integrated with contra rotating fans, sequential dual combustion chambers to facilitate "Energy Mix" in aviation and a Cryogenic Bleed Air Cooling System (CBACS). The current analysis focuses on three aspects: 1) effects of the CBACS on the HPT cooling air requirement and the associated effects on the cycle efficiency; 2) performance optimization of the hybrid engine; 3) assessment of the emission reduction by the hybrid engine. An integrated model framework consisting of an engine performance model, a turbine cooling model, and a Cryogenic Heat Exchanger (CHEX) model is used to perform the analyses. The parametric analysis shows that using the CHEX, the bleed air temperature can be reduced significantly (up to 600 K), which reduces the turbine cooling air requirement by more than 50%, while increasing the LNG temperature by 300K. Consequently, the cycle efficiency improves even further. Depending on the fuel flow distribution between two combustors. The CO_2 emission from the hybrid engine is lower by 15% to 30%. The mission analysis along with the Multi-Fuel Blended Wing Body aircraft shows a reduction in NOx emissions by 80% and CO_2 emission by 50% when compared to B-777 200ER.

Keywords: alternative fuels, low emissions, multi-fuel, new engine architecture

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1. INTRODUCTION

Aircraft emit gases such as carbon dioxide (CO_2), nitrogen oxide (NOx), water vapour, and particulates (soot), amongst which, CO_2, H_2O and NOx are responsible for Global Warming [1]. The water vapor emitted at high altitudes under certain atmospheric conditions condenses into droplets to form contrails, which are considered as one of the dominant greenhouse gases in the middle and upper troposphere [2]. Even though aviation shares only 3-5% of anthropogenic causes of Global Warming, the world civil aircraft fleet is expected to double by 2031 [3]. Consequently, the environmental impact of aviation will increase significantly. To develop sustainable civil aviation, the Advisory Council for Aeronautics Research in Europe (ACARE) has set ambitious objectives to reduce CO_2 emission by 75%, and NOx emissions by 90% by the year of 2050 when referring to the year 2000 technology [4].

There are different approaches which can reduce CO_2 emission significantly: 1) using propulsion architectures that are more efficient; 2) using alternative fuels that are more sustainable than kerosene. Innovative engine architectures, for instance, the Geared Turbofan [5], the Intercooled Recuperated Aero-engine [6], and the Open rotor [7] are examples of the first option. Even though the reduction in CO_2 this way is significant, it is not enough to meet the ACARE emission goals. Therefore, the latter option is drawing more attention.

There are several criteria in selecting a fuel for aviation. One of the main criteria is the energy density, as reducing weight and volume is of paramount importance for aviation. Both Specific Energy Density (SED, amount of energy per unit mass of the fuel) and Volumetric Energy Density (VED, amount of energy per unit volume) are important. In Figure 1, several energy sources in terms of their SED and VED are shown [8]. It can be seen that Jet-A / kerosene has good SED and VED and therefore is suitable for aviation. Moreover, Liquefied Hydrogen (LH2) has high SED but poor VED, implying that huge volume would be required to carry any reasonable amount of LH2. This makes it challenging to use LH2 in aviation. Additionally, using LH2 in aviation has several other challenges including safety, logistics, passenger perception, etc. Certainly, the advantages of using LH2 shouldn't be neglected as the CO_2 emission can be eliminated completely. The engine emits water vapour and some amount of NOx. From a long term perspective, LH2 is an ideal candidate for aviation, especially, to satisfy the imperative requirement for sustainability.

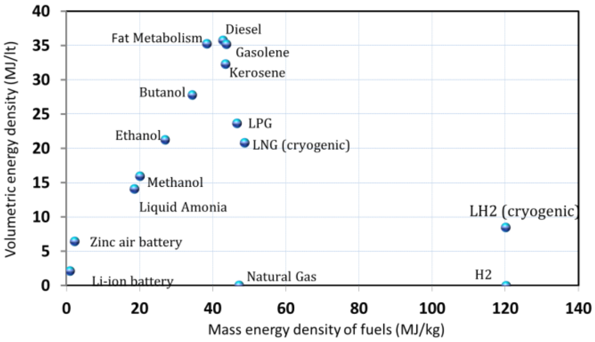

Figure 1: Comparison of various energy sources for aviation [8].

From Figure 1, it can be seen that Liquefied Natural Gas (LNG) is in between kerosene and LH2, both in terms of SED and VED. Currently LNG is one of the cheapest fuels available. The gas reserves in the world are enormous, especially with the discovery of shale gas, thus implying that LNG prices would be stable. Moreover, LNG is one of the cleanest fuels and recently it has been proved that LNG can also be generated by using renewable energy. The effects of using LNG are summarized below.

Advantages of LNG:

- Lower fuel weight compared to kerosene.
- Approximately 25 % reduction in CO_2 emission.
- Natural gas can be burnt at a lower equivalence ratio, which enables a substantial reduction in NOx formation.
- LNG is a cryogenic fuel and therefore a good heat sink. It can be used in a beneficial manner to enhance the thermodynamic efficiency of the engine, for instance by intercooling, bleed cooling, air-conditioning, etc.
- LNG is substantially cheaper than the conventional jet fuel.

Disadvantages of LNG:

- Requires pressurized tanks for storage, causing an increase in the aircraft Operating Empty Weight (OEW).
- Requires insulation to keep the fuel cool, increasing aircraft OEW further.
- Increased fuel storage space when compared to jet fuels.
- Airport facilities and logistics for storing and tanking the LNG are required.

To make use of the advantages provided by LNG and overcome the associated disadvantages, the multi-fuel hybrid engine concept has been proposed in the AHEAD project, aiming to lower NOx and CO_2 emissions. A schematic of the hybrid engine is depicted in Figure 2. The proposed hybrid engine has two combustors. In each combustor, different fuels (LNG & kerosene in the current paper) are burnt simultaneously. By varying the fuel flow rate individually, a different reduction rate in CO_2 emission can be realized. Moreover, a Cryogenic Bleed Air Cooling System (CBACS) is introduced in the hybrid engine to cool the air used for HPT cooling, thereby reducing the mass flow required HPT cooling. It is expected that in this way, the thermal efficiency of the engine cycle is improved. In addition, the reduction in the NOx emissions is achieved by the advanced combustion technique considered in the hybrid engine as well as low combustor operating temperatures achieved due to the distributed heat addition. The concept of this engine has been thoroughly discussed in [8]. In this paper, the performance of the hybrid engine will be assessed and compared with three turbofan engines, listed below.

- GE90-94B, representing an engine from the year 2000
- GEnx-1B64, representing the current SOA engine technology
- GTF-2035: an imaginary Very High Bypass Ratio (VHBR) turbofan engine.

2. MODEL FRAMEWORK

The model framework consists of an engine performance module and a Cryogenic Heat Exchanger (CHEX) module. These two modules are integrated as illustrated in Figure 2. Each module will be elaborated in this section.

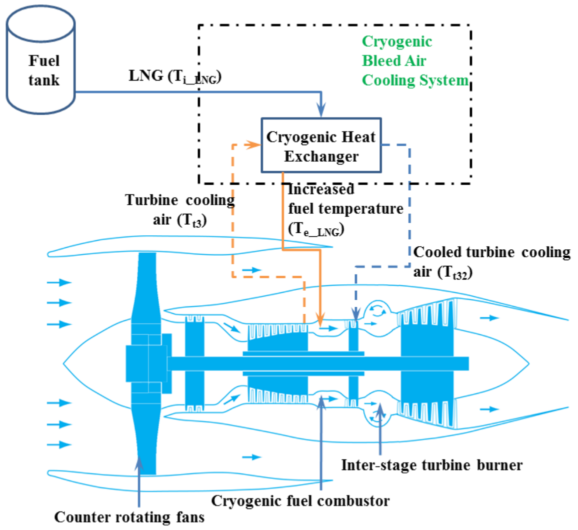

Figure 2: The schematic of the hybrid engine concept using LNG & Biofuel.

2.1 The engine performance module

A 0-D engine performance module is created using Gas Turbine Simulation Program (GSP) [9]. The module layout is shown in Figure 3. The main gas path of this module includes inlet, fan, Low Pressure Compressor (LPC), High Pressure Compressor (HPC), cryogenic combustion chamber (burning natural gas), two stage High Pressure Turbine (HPT), Inter-stage Turbine Burner (ITB, burning biofuel/kerosene), Low Pressure Turbine (LPT), core nozzle and bypass nozzle. The previous analysis has shown that the pressure loss in the bypass duct has a significant effect on the cycle efficiency. Therefore; an adiabatic duct (component 23 in Figure 3) has been used to account for the pressure loss in the bypass. The components efficiencies and the duct pressure loss at the design condition are given in Table 1. The mechanical efficiency of the low-pressure shaft considers the losses due to the gearbox.

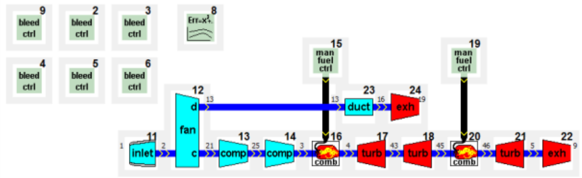

Figure 3: The engine performance model.

Furthermore, in the bleed control components, numbered as 2-6 and 9, the turbine cooling air requirement as a fraction of the core air mass flow rate is specified. These bleed control components are implicitly connected to the HPC by matching the bleed number. The component no. 8 controls the thrust requirement. The turbine cooling air requirement is calculated using an in-house turbine cooling module [10]. In the turbine cooling module, the maximum allowable metal temperature is assumed to be 1450 K.

Table 1: Baseline component performance parameters

Component	***Performance parameter***	***Notation***	***Datum value***	***Unit***
Fan	polytropic efficiency	η_{fan}	93	%
LPC	polytropic efficiency	η_{LPC}	93	%
HPC	polytropic efficiency	η_{HPC}	91	%
Main combustor	Combustion efficiency	η_{CC}	99.9	%
	pressure ratio	π_{CC}	0.95	[-]
HPT (uncooled)	polytropic efficiency	η_{HPT}	93	%
ITB	Combustion efficiency	η_{ITB}	99.7	%
	pressure ratio	π_{ITB}	0.97	[-]
LPT (uncooled)	polytropic efficiency	η_{LPT}	92.5	%
High pressure shaft	mechanic efficiency	η_{mHP}	99.5	%
Low pressure shaft	mechanic efficiency	η_{mLP}	99.3	%
Bypass duct	pressure loss	$\Delta p_t/p_{tin}$	2	%

2.2 Cryogenic Heat Exchanger Module

A CHEX module is introduced in the hybrid engine model framework. Through this heat exchanger, the bleed air is cooled by LNG before being used for HPT cooling. One of the noticeable phenomena observed in the CHEX is the phase change of LNG. When the temperature of LNG reaches its boiling point (120 K), LNG starts to transit from the liquid to the gas phase. This causes a significant change in the fluid properties and the heat transfer coefficient. The pressure drop also differs from that of a single-phase flow. The heat exchanger has been designed based on the input parameters specified in Table 2. They are pressure, temperature, and mass flow rate of both fluids at the inlet. The temperature of the bleed air at the exit is another design variable to determine the total heat to be transferred. The cycle performance calculation determines the mass flow rate of LNG and cooling air. The pressure drop of the bleed air should be lower much lower than the combustor pressure drop in order to enable successful mixing of the cooling air with the mainstream flow through the turbine. The design process of the LNG-air CHEX are discussed and presented in [11]. A shell-tube configuration with the counter-flow arrangement is considered following a typical two-phase flow heat exchanging mechanism.

Table 2: Specifications of heat exchanger design.

Design variables	***Values***
Inlet bleed air temperature, K	$\mathrm{T_{t3}}$
Exit bleed air temperature, K	600
Inlet fuel temperature, K	120
Inlet bleed air pressure, Bar	p_{t3}
Air/fuel mass flow rate, kg/s	Determined by cycle calculation
Bleed air pressure loss ($\Delta\mathrm{p}/\mathrm{p_{t3}}$), %	5≥

Once the heat exchanger is designed, it is convenient to consider the characteristics of a heat exchanger from the effectiveness point of view such that it can be easily implemented in an engine performance analysis framework. The definition of the heat exchanger effectiveness follows the ε-NTU method presented by Shah and Sekulic in [12]. Theoretically, the maximum temperature that LNG can attain is the inlet temperature of the air, whereas, the minimum temperature of the bleed air is the inlet temperature of LNG. This temperature difference together with the mass flow rate and the heat capacity of fluids determine the maximum heat flux, represented by Eqn. (1),

$$q_{\max} = \min\left\{\dot{m}_{air}\cdot\left(h(T_{t3}) - h(T_{i\_LNG})\right), \dot{m}_{LNG}\cdot\left(h(T_{t3}) - h(T_{i\_LNG})\right)\right\} \quad (1)$$

where min indicates the minimum heat flux between two fluids; h represents the specific enthalpy of given substance; $\dot{m}$ is the mass flow rate of given fluid; the subscript *3* indicates the inlet condition of the air, and i_LNG indicates the inlet condition of LNG. After defining the maximum heat flux, the effectiveness of the CHEX can be calculated by Eqn. (2),

$$\varepsilon = \frac{q}{q_{\max}} = \frac{\dot{m}_{LNG}\cdot(h(T_{e\_LNG}) - h(T_{i\_LNG}))}{q_{\max}} = \frac{\dot{m}_{air}\cdot(h(T_{t3}) - h(T_{t32}))}{q_{\max}} \quad (2)$$

where the subscripts *3* and *32* indicate the inlet and exit of the bleed air section (in line with Figure 2); e_LNG and i_LNG indicate the LNG at exit and inlet respectively.

3. RESULTS AND DISCUSSIONS

Before performing detailed analysis of the proposed hybrid engine, a variable named as ITB energy fraction is introduced (Eqn. (3)), which indicates a ratio of energy input in the first and the second combustor.

$$ITB\ energy\ fraction = \frac{\dot{m}_{\mathrm{kerosene}} \times LHV_{\mathrm{kerosene}}}{\dot{m}_{LNG} \times LHV_{LNG} + \dot{m}_{\mathrm{kerosene}} \times LHV_{\mathrm{kerosene}}} \quad (3)$$

where LHV is the Lower Heating Value of given fuel. It represents the energy fraction of the kerosene over the total energy provided by both fuels.

The performance requirements of the hybrid engine at different operating points are given in Table 3. These values are derived from the thrust requirements of the Multi Fuel Blended Wing Body (MF-BWB) aircraft.

Table 3: The performance requirements from hybrid engine.

Operating points	***Ambient condition***	***Mach number***	***Thrust [kN]***
Max static	SLS ISA	0	280
Take-off	SLS ISA	0.2	250
TOC	12km, ISA	0.8	56
Cruise	12km, ISA	0.8	50
Ground idle	SLS ISA	0	20

3.1 Parametric analysis

Parametric analysis has been conducted for cruise condition to understand the effects of the CHEX effectiveness on the bleed air temperature and the resulting variation in the turbine cooling air requirement. The datum engine cycle at cruise is given in Table 4.

Table 4: Datum engine cycle for parametric analysis.

Variables	***Notation***	***Datum value***	***Unit***
Fan pressure ratio	FPR	1.5	[-]
Bypass ratio	BPR	15	[-]
Overall Pressure Ratio	OPR	70	[-]
HPT inlet temperature	Tt4	1689	K
ITB energy fraction	[-]	0.1	[-]

In Figure 4 a), the variation in the bleed air temperature versus the heat exchanger effectiveness is illustrated. As the effectiveness (ε) increases, the heat flux increases. Therefore, the bleed air temperature reduces by approximately 200K at an ε = 0.3 to about 600 K at an ε = 0.7. The change in the turbine cooling air requirement is illustrated in Figure 4 b). The solid curve represents a baseline hybrid engine without a CHEX. A contemporary hybrid engine with CHEX and effectiveness of 0.3 and 0.5 are presented. Using CHEX with ε = 0.3 reduces the turbine cooling air requirement by half. However, increasing ε from 0.3 to 0.5 results in only moderate reduction of the turbine cooling air. Another observation is that the reduction rate decreases with the reduction in the turbine cooling air mass flow rate, implying that CBACS is more effective for engines with higher turbine inlet temperature.

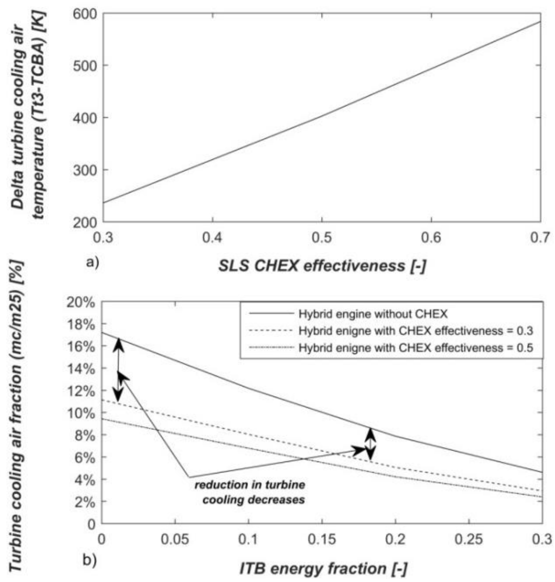

Figure 4: a) variation in the bleed air temperature; b) variation in the turbine cooling air fraction.

With the turbine cooling air requirement determined, the fuel temperature can also be computed. The effect of heat exchanger effectiveness at cruise and at SLS on fuel temperature is presented in Figure 5. The heat exchanger effectiveness (ε) is varied from 0.3 to 0.7 for both SLS and cruise conditions. The grey scale represents the variation in the LNG temperature (K). The max fuel temperature is obtained when the CHEX ε maximum at cruise but minimum at SLS. This is because as the heat exchanger ε at cruise increases, the heat flux through the heat exchanger increase thereby increasing the temperature of LNG.

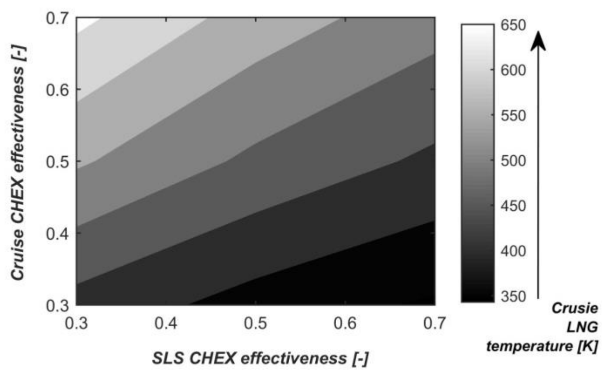

Figure 5: Variation in the temperature of LNG.

Although higher turbine cooling air requirement penalizes the cycle thermal efficiency, the increase in LNG temperature has more effect on the cycle efficiency. The variation in the thermal efficiency for cruise condition is presented in Figure 6. It can be seen that the increase in LNG temperature has a strong influence on the cycle efficiency.

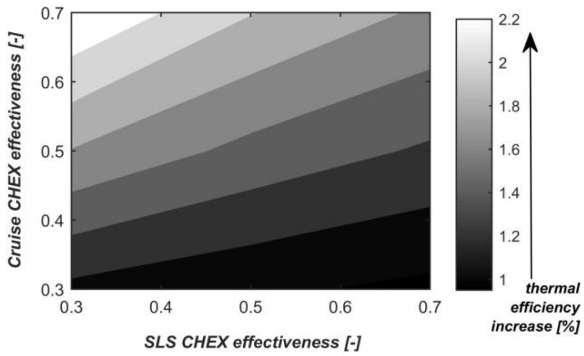

Figure 6: Variation in thermal efficiency.

Considering the results presented in Figure 5 and Figure 6, it can be concluded that the CHEX should be designed for cruise condition to ensure highest heat exchanger effectiveness. Therefore, the LNG-air CHEX in the current paper has been designed at cruise condition. The effectiveness at off-design condition is iterated from a performance map which has been derived from the heat exchanger characteristics.

3.2 The engine performance optimization

The cycle optimization is performed to minimize the cruise specific fuel consumption. The design space is defined in Table 5. The optimization is executed at the ITB energy fraction from 0 to 0.3. The inlet mass flow rate remains constant. The MATLAB fmincon optimizer using Sequential Quadratic Programming (SQP) method is used. The fundamentals of the SQP algorithm has been thoroughly discussed by Nocedal and Wright in [13]. The optimization results of the multi-fuel hybrid engine are presented in the following paragraphs.

3.2.1 Performance of the baseline engine

The three baseline engines listed earlier have been used for the comparison purpose. The performance of these engines at cruise condition is displayed in Table 6. The CO_2 and H_2O emission are determined assuming a complete combustion process.

Table 5: Bounds and constraints of design parameters.

Bounds of design parameters		***Constraints***	
FPR	[1.2, 1.5]	OPR	<= 70
LPC pressure ratio	[1.4, 5.0]	FN [kN]	= 50
HPC pressure ratio	[8, 20]	Inlet mass flow rate [kg/s]	constant
HPT inlet temperature (Tt4) [K]	[1400, 1900]		
BPR	[8, 15]		

Table 6: The baseline engine performance at cruise condition.

	GE90-94B	***GEnx-1B64***	***GTF-2035***
Design Parameters			
BPR	8.6	9.1	15
FPR	1.62	1.65	1.44
OPR	39	41	70
T_{t4} [K]	1447	1438	1900
Engine Performance			
Thermal efficiency [%]	45	46.7	50.2
Propulsive efficiency [%]	81.2	82.6	83.0
TSFC $[g/kN/s]$	14.7	14.1	13.2
Kerosene $[kg/s]$	1.14	0.76	0.66
CO_2 emission $[kg/s]$	3.6	2.40	2.09
H_2O emission $[kg/s]$	1.41	0.94	0.82

3.2.2 Performance of the hybrid engine

The performance of the hybrid engine is presented in Table 7. The bleed air temperature and the LNG temperature varies with the ITB energy fraction. As the ITB energy fraction increases, the HPT inlet temperature reduces from 1593 K to 1387K. The LPT inlet temperature of each engine remains nearly constant at around 1200 K. The thermal efficiency reduces as the ITB energy fraction increases, whereas, the propulsive efficiency remains constant. The mass flow rate of LNG reduces and the mass flow rate of kerosene increases with increase in the ITB energy fraction. Figure 7 shows the comparison between hybrid engine and baseline engines for different ITB energy fractions. Comparison of the cycle thermal efficiency, CO_2 emission, and H_2O emission can be seen in in Figure 7. Compared to GE90 and GEnx engines, the thermal efficiency of the hybrid engine is higher by 17% and 12% respectively. Compared to the GTF-2035, the thermal efficiency is higher by approximately 5%. This is mainly due to the utilization of LNG as a fuel. As the ITB energy fraction increases, the thermal efficiency of the hybrid engine reduces gradually. For an ITB energy fraction of 0.3, the thermal efficiency of hybrid engine is lower than that of the GTF-2035 engine. The propulsive efficiency of the hybrid engine is similar to the baseline engines. The CO_2 emission of the hybrid engine is approximately 20% lower than GTF-2035, 30% lower than GEnx, and more than 50% lower than GE90. However, burning LNG results in more water vapor emission as compared to the baseline engines.

Table 7: The optimized hybrid engine.

	ITB energy fraction			
	0	***0.1***	***0.2***	***0.3***
Design Parameters				
BPR	15	15	15	15
FPR	1.48	1.48	1.48	1.48
LPC pressure ratio	5	5	5	5
HPC pressure ratio	9.48	9.48	9.48	9.48
HPT inlet temperature [K]	1593	1521	1451	1387
LPT inlet temperature [K]	1177	1187	1200	1215
Engine Performance				
Thermal efficiency [%]	52.5	51.7	50.7	49.7
Propulsive efficiency [%]	82.6	82.6	82.6	82.6
LNG [kg/s]	0.54	0.50	0.45	0.40
Kerosene [kg/s]	0	0.06	0.13	0.20
Bleed air temperature [K]	602	603	604	604
LNG temperature [K]	528	478	424	366
CO_2 emission [kg/s]	1.49	1.57	1.65	1.74
H_2O emission [kg/s]	1.22	1.2	1.17	1.15

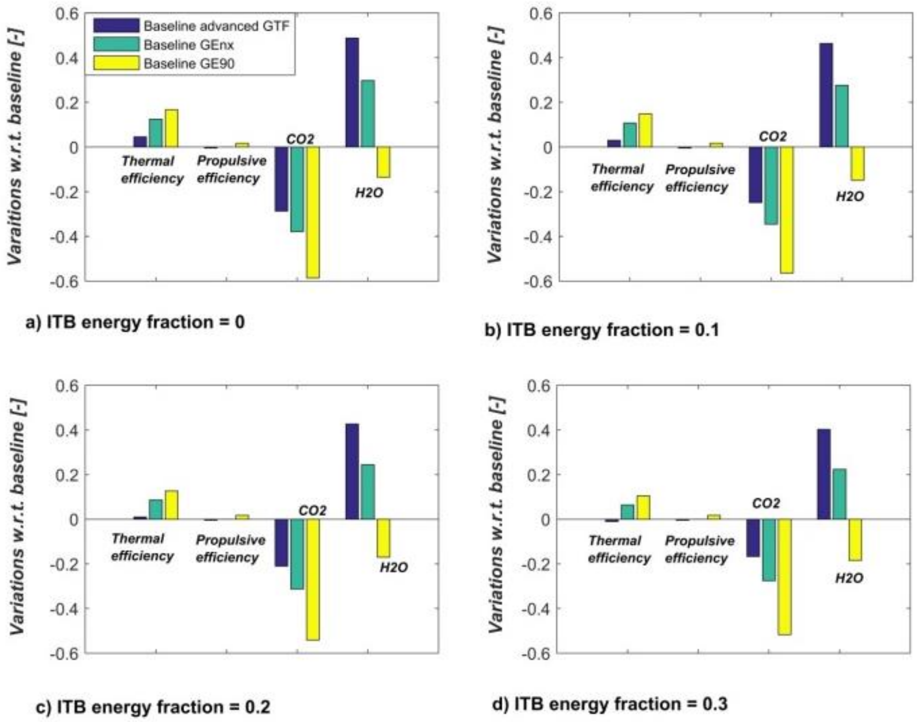

Figure 7: Comparison of the LNG-kerosene hybrid engine to baselines.

3.3 Mission analysis

This section focuses on the performance of the hybrid engine with MFBWB aircraft for various missions. A schematic of the MFBWB together with the hybrid engine is shown in Figure 8.

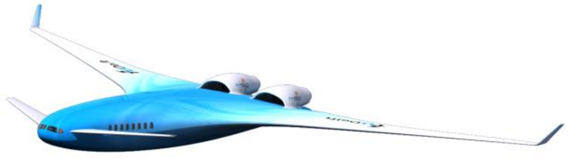

Figure 8: Schematic of the MFBWB concept.

Three city pairs, representing different flight missions are presented here. For the purpose of comparison, long range Boeing 787-8 and Boeing 777-200ER have been selected as baseline aircraft, representing year 2000 and 2015 technology respectively.

Piano X [14] is used to generate mission profiles for B787 and B777. With this calculation tool, emissions of an existing aircraft for a given flight mission can be predicted with fairly good accuracy. The NOx emissions of the hybrid engine are calculated using the emission prediction tool for the hybrid combustion system [15]. The CO_2 emission and H_2O emission are derived based on the fuel usage. The results for various aircraft models are presented in Table 8 - Table 10. The comparison is presented in Figure 9 and Figure 10. The engine has to perform under various conditions. If the engine cannot meet the performance requirement, the engine design has to be modified. The characteristics of the hybrid engine at several off design conditions were verified. The performance requirements are presented in Table 3.

Table 8: Emissions and energy consumption per payload per unit distance (SYD-DXB 12000km).

	B777-200ER	***B787-8***	***LNG-kerosene BWB***
Energy consumption, kJ/payload/km	8.3	7.1	4.95
NOx emission, mg/payload/km	3.12	1.93	0.4
CO2 emission, mg/payload/km	610.65	522.78	297.45
H2O emission, mg/payload/km	242.32	207.45	201.58

Table 9: Emissions and energy consumption per payload per unit distance (AMS-EZE 11000km)

	B777-200ER	***B787-8***	***LNG-kerosene BWB***
Energy consumption, kJ/payload/km	7.63	6.54	4.77
NOx emission, mg/payload/km	2.89	1.81	0.38
CO2 emission, mg/payload/km	561.5	481.4	286.7
H2O emission, mg/payload/km	222.8	191	194.3

Table 10: Emissions and energy consumption per payload per unit distance (MAD-PVG 10000km)

	B777-200ER	***B787-8***	***LNG-kerosene BWB***
Energy consumption, kJ/payload/km	6.62	5.78	4.67
NOx emission, mg/payload/km	2.56	1.6	0.36
CO2 emission, mg/payload/km	487.5	425.2	280.7
H2O emission, mg/payload/km	193.4	168.7	190.2

In Figure 9, it can be observed that compared to B777-200ER, the proposed LNG-kerosene MF-BWB aircraft can reduce the NOx emissions by more than 80%, CO_2 by 50%, and H_2O by 20%. The total energy consumption is lower by 40% for the MFBWB aircraft.

When compared to the B787-8, a similar trend can be observed as depicted in Figure 9. An exception is observed for the H_2O. As the mission range decreases, the LNG-kerosene BWB might emit more H_2O than B787-8.

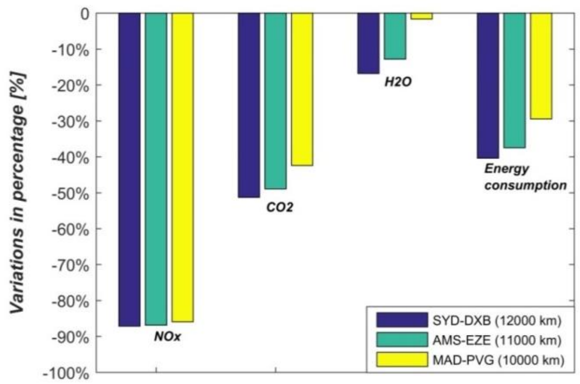

Figure 9: Comparison of the LNG-kerosene BWB to B777.

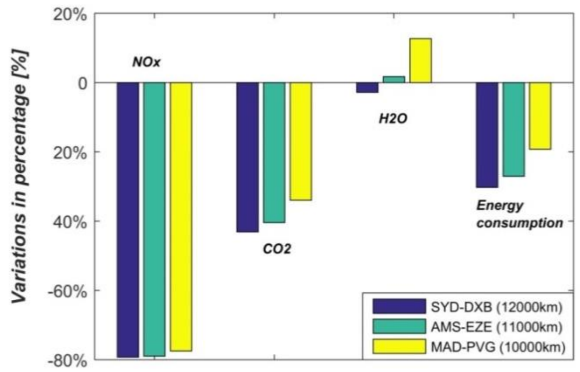

Figure 10: Comparison of the LNG-kerosene BWB to B787.

4. CONCLUSIONS

This paper presents the performance analysis of the multi-fuel hybrid engine. Following conclusions can be drawn from the research carried out:

- Using LNG as a fuel helps to improve the cycle efficiency and specific thrust.
- Using LNG, the bleed air temperature can be reduced by 200 K to 600K, depending on the heat exchanger effectiveness (0.3 to 0.7). This temperature decrease results in reduction of the turbine cooling air requirement by 50%.
- Compared to the current state of the art turbofans, the hybrid engine can reduce CO_2 emission by 30%.
- At lower ITB energy fraction, the thermal efficiency of the proposed hybrid engine is around 5% better when compared to a hypothetical GTF engine of 2035. However, the benefits reduce as the ITB energy fraction increases.
- Compared to B777-200ER, the LNG-kerosene MF-BWB reduces the NOx emissions by more than 80%, CO_2 emission by 50% and a slight reduction in H_2O emission.
- Compared to B787-8, the maximum reductions in the NOx emissions, CO_2 emission and the energy consumption are about 80%, 40% and 30% respectively. However there is a slight increase in the H_2O emission.
- The hybrid engine along with MF-BWB aircraft paves a new approach to make aviation more sustainable.

5. ACKNOWLEDGMENT

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6. FUNDING

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