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Performance assessment of a multi-fuel hybrid engine for future aircraft

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A R T I C L E I N F O

Article history:
Received 7 September 2017
Received in revised form 25 February 2018
Accepted 5 March 2018
Available online xxxx

Keywords:
Hybrid engine
Multi-fuel
Optimization
Performance assessment
Low emissions

A B S T R A C T

This paper presents the performance assessment of a novel turbofan engine using two energy sources: Liquid Natural Gas (LNG) and kerosene, called Multi-Fuel Hybrid Engine (MFHE). The MFHE is a new engine concept consisting of several novel features, such as a contra-rotating fan to sustain distortion caused by boundary layer ingestion, a sequential dual-combustion system to facilitate "Energy Mix" in aviation and a Cryogenic Bleed Air Cooling System (CBACS) to cool the turbine cooling air. The MFHE has been envisaged as a propulsion system for a long-range Multi-Fuel Blended Wing Body (MFBWB) aircraft. In this research, we study the uninstalled characteristics of the MFHE covering three aspects: 1) the effects of CBACS on the High Pressure Turbine (HPT) cooling air requirement and its consequence on the engine cycle efficiency; 2) the cycle optimization of the MFHE; 3) the performance of the MFHE at a mission level. An integrated model framework consisting of an engine performance model, a sophisticated turbine-cooling model, and a CBACS model is used. The parametric analysis shows that using CBACS can reduce the bleed air temperature significantly (up to 400 K), thereby decreasing the HPT cooling air by more than 40%. Simultaneously, the LNG temperature increases by more than 200 K. The hybrid engine alone reduces the CO_2 emission by about 27% and the energy consumption by 12% compared to the current state-of-the-art turbofan engine. Furthermore, the mission analysis indicates a reduction in NOx emission by 80% and CO_2 emission by 50% when compared to the baseline aircraft B-777 200ER.

1. Introduction

Aviation contributes to 5% of the total anthropogenic climate change including both the CO_2 effects and the non-CO_2 effects from NO_x emissions, water vapor and contrails [1]. The demand for air transportation is anticipated to grow by 4.6% annually for the next 20 years [2], which aggravates the aviation's climate impact. To enable the sustainable growth, the Advisory Council for Aeronautics Research in Europe has set ambitious objectives to reduce CO_2 emission by 75% and NO_x emissions by 90% by the year 2050 when compared to the year 2000 technology [3].

The CO_2 reduction can be achieved in a combination with innovative aircraft/engine technologies and using alternative fuels. The Geared Turbofan [4], the Intercooled Recuperated Aero-engine [5], and the Open rotor [6] are examples of the efficient engine concepts. Whereas, the NO_x emissions can be reduced by the innovative low NO_x combustion techniques and by using hydrogen-rich alternative fuels.

One of the other main challenges for future aviation is the energy source. Currently, aviation consumes around 1 Billion liters of Jet Fuel every day [7,8] and it is anticipated to increase with the increase in air traffic despite the improvement in aircraft efficiency. On the other hand, the oil reserves are depleting, thus creating a discrepancy in the supply and demand, which will lead to a significant increase in the fuel cost. This increase in fuel cost has already increased the fuel share in the total operating cost of an airline to around 30% [9]. Further increase in fuel prices would have negative consequences for airlines. Therefore, other means of energy source to drive the aircraft engines will have to be tapped. Though the usage of sustainable alternative fuels in the aviation industry is not widely practiced, some commercial flights have been successfully operated with biofuels [10,11]. Furthermore, the emissions standard set by the International Civil Aviation Organization for engine certification is becoming stringent. As long as the conventional fuel is in use, the goal of reducing CO_2 emission significantly remains illusive; hence, alternative fuels will play an important role.

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https://doi.org/10.1016/j.ast.2018.03.005
1270-9638/

Nomenclature

Abbreviations

BPR	Bypass Ratio	
CBACS	Cryogenic Bleed Air Cooling System	
CHEX	Cryogenic Heat Exchanger	
EF	Energy Fraction	
EI	Emission Index	g/kg kg/kg
FPR	Fan Pressure Ratio	
HPC	High Pressure Compressor	
HPT	High Pressure Turbine	
ITB	Inter-stage Turbine Burner	
LNG	Liquefied Natural Gas	
LH2	Liquefied Hydrogen	
LHV	Lower Heating Value	J/kg
LPC	Low Pressure Compressor	
LPT	Low Pressure Turbine	
MFBWB	Multi-Fuel Blended Wing Body	
MFHE	Multi-Fuel Hybrid Engine	
OPR	Overall Pressure Ratio	
SED	Specific Energy Density	
SLS	Sea Level Static	
TOC	Top of Climb	
VED	Volumetric Energy Density	
VHBR	Very High Bypass Ratio	

Symbols

$\dot{m}$	Mass flow rate	kg/s
p_t	Stagnation pressure	Bar
T_t	Stagnation temperature	K
η	Efficiency	
π	Pressure ratio	
ε	Heat exchanger effectiveness	

Subscripts

3	High pressure compressor exit
4	High pressure turbine inlet
46	Low pressure turbine inlet

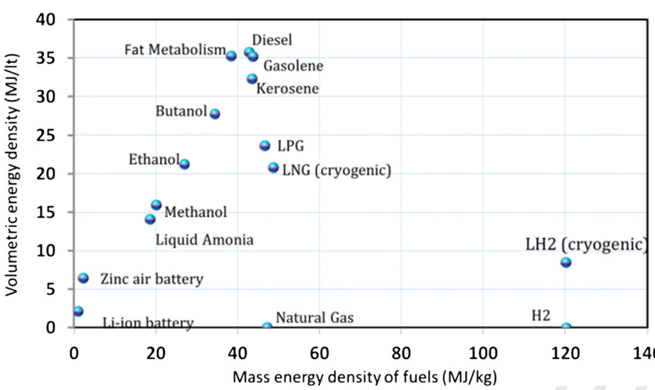

Fig. 1. Comparison of various energy sources for aviation [12].

2. Fuel selection

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, the amount of energy per unit volume) are essential. In Fig. 1, various energy sources regarding their SED and VED are presented [12]. It can be seen that Jet-A/kerosene has good SED and VED and therefore 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 other challenges like safety, logistics, etc. [13]. Certainly, the advantages of using LH2 should not be neglected as the CO_2 emission can be eliminated. Moreover, hydrogen should not be viewed as fuel but as an energy carrier (e.g., high-energy dense battery). From a long-term perspective, LH2 can be a good candidate for aviation, especially, to satisfy the imperative requirement for sustainability.

Furthermore, the Liquefied Natural Gas (LNG), which primarily consists of methane, has drawn considerable attention. LNG is natural gas that has been liquefied form to increase energy density and avoid pressurization. From Fig. 1, it can be seen that LNG lies in between kerosene and LH2, both in terms of SED and VED. Currently, LNG is one of the cheapest fuels available [14]. The global reserves of natural gas are enormous, thus implying that the LNG price would be stable. Moreover, LNG is one of the cleanest fuels, and recently it has been shown that LNG can also be generated by using renewable energy [15,16]. The effects of using LNG for civil aviation are summarized below.

Advantages of LNG:

- Approximately 25% reduction in CO_2 emission for the same energy consumption
- The natural gas can be mixed with air in a better way than kerosene, which reduces NOx emission.
- LNG is a cryogenic fuel and therefore a good heat sink. It can be used beneficially to enhance the thermodynamic efficiency of the engine, for instance by intercooling, bleed cooling, air-conditioning, etc.
- LNG is cheaper than the conventional jet fuel in terms of MJ/$.
- The energy density of LNG is higher than kerosene

Disadvantages of LNG:

- Unlike kerosene, LNG cannot be stored in wings.
- LNG has to be stored in insulated cylindrical or spherical tanks, increasing the aircraft operating empty weight.
- The volumetric energy density of LNG is lower compared to kerosene.
- Airport facilities and logistics for storing and tanking LNG are required.
- The H_2O emission (an import greenhouse gas at higher altitudes and latitudes) of burning LNG is higher compared to kerosene.

3. The multi-fuel blended wing body aircraft

Cryogenic fuels, like LNG, need to be stored in insulated cylindrical or spherical tanks with the well-insulated system to prevent them from leaking and boiling off. Therefore, the volume required to carry cryogenic fuels increases significantly, which makes it challenging for conventional aircraft. The Blended Wing Body (BWB) concept provides possibilities for cryogenic fuels as far as space is concerned. The BWB has been studied by many researchers world widely [17–20]. The MFBWB concept proposed in

Please cite this article in press as: F. Yin et al., Performance assessment of a multi-fuel hybrid engine for future aircraft, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.03.005