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Long range transport aircraft using hydrogen fuel

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ABSTRACT

Hydrogen is since long seen as an outstanding candidate for an environmentally acceptable, future aviation fuel. Given that most comprehensive studies on its use in aviation were performed over two decades ago, the current article evaluates its potential as a fuel for long range transport aircraft at current and future technology levels. The investigations show that hydrogen has the potential to reduce the energy utilisation of long range transport aircraft by approximately 11%. The use of hydrogen namely allows a much smaller wing area and span since the wing size is not restricted by its fuel storage capacity. At a given price per unit energy content, the smaller wings lead to a reduction of around 30% in take-off gross weight and 3% in direct operating costs for a given fuel price per energy content. The hydrogen-fuelled aircraft are furthermore slightly more sensitive to a possible reduction in operating empty weight in the future and 20% less sensitive to further improvements in engine thrust specific fuel consumption.

1. Introduction

Civil aviation faces a mounting conflict to sustain growth in a way that meets the needs of society while aiding to protect the environment. Aviation is projected to be the fastest growing industry for the next two to three decades with global growth spurred by emerging-market economies [1,2]. An average annual increase in revenue passenger miles of around 5% is foreseen, and the fleet size will double over the next 20 years [1–3]. There is no realistic prospect that gains in aircraft energy efficiency will continue to be sufficient to compensate for the increase in emissions of greenhouse gases due to this anticipated growth [4]. The aviation industry has additionally set itself an aggressive target to reduce aviation emissions by at least 50% by 2050 [1]. As a consequence, the forecasted growth might be undermined by restrictions imposed to limit greenhouse gas emissions.

Hydrogen (H_2) offers the potential to alleviate or maybe even completely avoid such restrictions. When entirely produced through electrolysis powered from renewable or nuclear energy, the use of H_2 namely strongly reduces both airborne as well as complete "well to wing" emissions, with contrails and contrail cirrus as the only remaining significant contributor to climate change [5–12]. As a versatile energy carrier that can be produced from a wide range of primary energy sources, H_2 can additionally improve the reliability of the fuel supply for aviation [8] as it could remove the geopolitical tensions associated with the concentration of fossil fuel resources in a small geographical region.

This energy security perspective has historically been the primary impetus for investigations into the use of hydrogen [13]. Hydrogen has been considered as an aviation fuel from as early as 1918 [14]. Whereas the bulk of the studies were theoretical [13,15–22], flight tests were conducted in the fifties using a B-57 airplane [23] and in the eighties using an experimental Tupolev Tu-155 aircraft, modified from a Tu-154 [24]. In both cases, only one of the engines was converted to run on cryogenic liquid hydrogen (LH_2). In 2000, the European

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Nomenclature

$\dot{m}_{air}$	air flow rate
¢	dollar cents
BPR	by-pass ratio
ESFC	energy specific fuel consumption
FLOPS	flight optimisation system
FPR	fan pressure ratio
H_2	hydrogen
LH_2	liquid hydrogen
LHV	lower heating value
OPR	overall pressure ratio
TIT	turbine inlet temperature
TSFC	thrust specific fuel consumption
USD	United States dollar

Commission funded the Cryoplane study for the system analysis of hydrogen-fuelled aircraft. Different aircraft configurations were studied using a minimal change approach where the wing platform and engine design were unaltered when converting from kerosene to hydrogen [19]. The study concluded that, due to the excessive tank volume required for LH_2, energy consumption would increase with 9–14% depending on the aircraft type [19]. This is in contrast with earlier studies [13,17,18,20,21] where energy utilisation for hydrogen is lower than for kerosene and is most likely related to the minimal change approach. Recent work additionally explored possible synergies with the current shift towards more electric aircraft, where hydraulic and pneumatic systems are replaced with electrical systems. The use of fuel cells as a replacement for the aircraft's auxiliary power unit has received a growing interest [25–27] and the use of hydrogen as fuel for the aircraft's main engines and its on-board storage in large quantities could benefit the development of such technologies.

Given that most studies of the LH_2 fuelled aircraft are over 2 decades old, and that the Cryoplane study adopted a minimal change approach which might bias the outcomes, the current work investigates the technological potential of hydrogen as a fuel for long range transport aircraft. The main aim of this study is to identify the technology areas where further research should focus on if the transition to a truly sustainable aviation fuel would come forth. Kerosene and hydrogen long-range aircraft are therefore compared at current and future aircraft technology levels. Large long-range aircraft are selected as their large fuel loads represents an upper limit to potential performance improvements from the adoption of hydrogen. The first section of this work details the methodology used for the aircraft designs for both fuels. The main focus of this section lies on the modifications required to model hydrogen-fuelled aircraft and engines. The results of wing sizing studies for large long range transport aircraft at current technology levels are given next. The wing is independently sized for both fuels to identify the optimum wing area and aspect ratio. The resulting designs are used as a baseline to assess the impact of technological progress in section 4.

2. Methodology

In the current study, two simulation tools, FLOPS and Gasturb, are employed. The FLight OPtimisation System (FLOPS) is a multidisciplinary aircraft preliminary design and analysis package developed by the NASA Langley Research Center [28,29]. FLOPS predicts the overall performance, weight, cost, and environmental factors needed for advanced concept evaluations. As FLOPS is a well-developed preliminary design platform, the bulk of the code is used as is. The component weight correlations used in FLOPS were however derived using a database of 17 transport aircraft that first flew between the late fifties and early eighties [29]. A structural technology improvement factor of 0.84 has therefore been applied to the individual weight items that comprise the aircraft empty weight to yield a technology level representative of a 2010 entry into service. The value of this factor is derived using data from the Cryoplane study [30,31].

When using FLOPS to model the hydrogen-fuelled aircraft a number of additional modifications are however required. Given its cryogenic nature, the LH_2 is stored in tanks located in the aircraft fuselage [10,15–21,32], as shown on Fig. 1. As a consequence, the fuselage length is a function of the fuel required for the mission and FLOPS is run iteratively until convergence occurs on the fuel weight and fuselage length. The fuel tank length and weight are determined using the method described in [32] and the fuel tank weight is added to the empty weight calculated by FLOPS. An additional 6% weight penalty is also applied to the fuselage weight to account for the structure to attach the main structure of the integral tank to the structure of the remainder of the fuselage [18]. The integration of the tanks in the fuselage presents a safety advantage as in this arrangements the tanks present a far smaller area for frontal impact than wing tanks and they are protected by a significant amount of structure, both ahead and beneath them [18].

The presence of the fuel tanks in the fuselage however not only affects the size and weight of the fuselage. Since the fuel is not stored in the wing as it is the case for kerosene, the bending moment alleviation effect of the fuel weight is no longer present, which leads to an increased wing weight. The magnitude of this increase is estimated using the inertia relief factor of the wing weight correlation from [33]. This factor, which accounts for the presence of fuel and engines on the wing, is used to update the bending material weight of the wing weight calculation of FLOPS [29]. For the range of wing areas under consideration the bending material weight increased by 37% on average. This results in an overall wing weight increase of around 6%.

The engine deck embedded in FLOPS cannot be used for the hydrogen fuel, so an external engine deck is generated in Gasturb 12 for both fuels [34]. The selected engine is representative of a 3 spool engine of the Rolls-Royce Trent family and is based on [35]. This particular engine is selected as exhaustive data is available on this validated model [35]. Table