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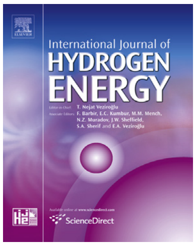

On the energy efficiency of hydrogen-fuelled transport aircraft

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ABSTRACT

Hydrogen could provide a pathway to long-term sustainable aviation provided its use does not excessively penalise aircraft performance and energy efficiency. To assess the implications of hydrogen use in aviation a study on the energy efficiency of kerosene- and hydrogen-fuelled aircraft is presented. The investigation shows that the use of hydrogen for long-range operation can lead to an increase in energy efficiency of up to 12% compared to kerosene. For short-to-medium-range aircraft, on the other hand, the adoption of hydrogen leads to an increase in the mission energy requirement of 5–18%. Storing hydrogen on top of the cabin instead of in tanks located in front and aft of it has a considerable impact on the energy efficiency. The increased weight of the top tanks leads to an increase in energy use of 6 and 19% for the selected notional short-respectively medium-range aircraft.

Introduction

Civil aviation is confronted with the incongruity to sustain growth while minimising its environmental impact. Aviation is namely forecasted to be the fastest growing industry with an annual increase in revenue passenger miles of 5% [1,2] and there is no realistic potential for gains in aircraft energy efficiency to outpace this predicted growth rate [3].

As fuel prices will most likely continue to rise, fuel is bound to become an increasingly large element in aircraft operating costs [4] and energy use will thus, in all likelihood, gain importance in the design of the next generation of aircraft. This changed design space with increasing environmental and economic pressure has lead to the resurgence of a variety of unconventional aircraft configurations and technologies like blended wing body aircraft [5,6], natural laminar flow [6,7], open rotor engines [6,8] and alternative fuels such as hydrogen [9–12]. Conceiving the next generation of aircraft for a (reduced) design range that matches the actual aircraft use has been explored as a parallel and potentially shorter-term pathway to reduce the fuel bill, operating cost and environmental footprint compared to a conventionally designed fleet [13–17].

This paper intends to unify those two streams of research. This is pursued by applying an aircraft design synthesis code across a range of transport aircraft sizes and design ranges for both kerosene and hydrogen-fuelled aircraft. For each fuel the aircraft are optimised for energy (fuel) efficiency and the impact of the fuel selection on this efficiency is explored. This provides, for the first time, a consistent and systematic evaluation of the impact of the choice of hydrogen fuel on aircraft energy efficiency. The methodology used for the investigations reported here is succinctly described in the next section. A comparison between kerosene- and hydrogen-fuelled short-, medium- and long-range aircraft is then

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Table 1 – Mission parameters for the different aircraft categories.

Category	Range [km]	Nr. Pax [–]	Mach Nr [–]	Ceiling [ft]	Field length [ft]	V_{app} [kts]
Short range	4,000	150	0.80	39,000	7,000	135
Medium range	9,000	300	0.82	41,000	9,000	140
Long range	14,000	400	0.84	43,000	12,000	150

made and the impact of the use of hydrogen tanks on top of the passenger cabin instead of integral tanks in front and aft of the cabin is investigated.

Methodology

The current study is performed using two simulation tools: FLOPS and Gasturb. The Flight Optimisation System (FLOPS) is a multidisciplinary aircraft preliminary design and analysis package [18,19] whose applicability for the type of analysis used in this article has been demonstrated previously [12,14,16]. FLOPS is an aircraft configuration optimisation program developed for use in conceptual design of new aircraft and in the assessment of impact of advanced technology [18]. It contains modules for preliminary weight estimations, preliminary aerodynamics, detailed mission performance, takeoff and landing and noise and cost analysis. The weight equations used to estimate component weights are developed using a non-linear least squares regression analysis on data from existing aircraft. The aerodynamics module uses a modified version of the empirical drag estimation technique with the inclusion of the Sommer and Short T method for skin friction calculations [18,19]. Mission performance is calculated using a step integrated technique based on energy levels and gradient-based non-linear optimisation is performed as a series of minimisation drawdowns with successively lowered values for the Fiacco-McCormick penalty function factors. The internal optimisation algorithm uses the Broyden-Fletch-Goldfarb-Schano (BFGS) algorithm for a design space that can consist of up to 18 parameters [19].

For the investigations reported in this article, the internal optimisation module of FLOPS is used to size the wing area, wing taper ratio and engine thrust for minimum fuel (energy) consumption. A minimum taper ratio is imposed as a function of the wing aspect ratio and sweep [20], whereas no external constraints are applied to the wing area and engine thrust. The wing sweep and thickness depend on the cruise Mach number of the aircraft [21], and the aspect ratio is limited to avoid high speed pitch-up [22,23]. Tailplanes are sized externally from FLOPS to obtain adequate handling qualities across the range of aircraft sizes [14,24].

To ensure compliance with current industry practise, mission parameters are adjusted to the design range and passenger capacity of the aircraft. The parameters adopted for the different classes are given in Table 1 (based on refs. [13,25–27]). All aircraft are set-up in a 2-class cabin configuration with 15% passengers (pax) in business class which has a seat pitch of 36 inch (91.4 cm). Economy seat pitch is set as 32 inch (81.3 cm) [25–27]. Passenger weight is taken as 74.8 kg (165 lbs) with an allowance of 20.0 kg (44 lbs) for baggage. The 150-pax kerosene-fuelled aircraft use a narrow-body configuration with 4 seats abreast in business and 6 abreast in economy, while both the 300 and 400 passenger aircraft are wide-body aircraft with 10 seats abreast in economy [25–27]. When using hydrogen, the cabin is modified to avoid excessive fuselage lengths. For the 150 and 300 pax aircraft this leads to a 7 respectively 11 abreast seating arrangement in economy. The hydrogen-fuelled aircraft with 400 passengers is subjected to a more radical change and a double deck cabin is employed as single deck arrangements lead to fuselage lengths in excess of 95 m.

Whereas this cabin configuration might deviate slightly from common airline practise, a common set of standards is adopted to ensure impartiality between the different designs, hence isolating the effect of aircraft size and design range on fuel efficiency. For the investigations reported here, the design payload-range combination is taken as the intersection between the maximum take-off weight limited portion of the payload-range diagram and the fuel capacity limit, as shown in Fig. 1.

When using FLOPS to model the hydrogen-fuelled aircraft a number of modifications are required. Given its cryogenic nature, the liquid hydrogen (LH_2) is namely typically stored in tanks located in the aircraft fuselage [10–12,28–34]. As a consequence, the fuselage length depends on the mission fuel weight and FLOPS is run iteratively until convergence occurs on the fuel weight and fuselage length. The fuel tank length and gravimetric efficiency are determined using the method described in Ref. [11]. The gravimetric efficiency η_{grav} is defined as

$$\eta_{grav} = \frac{W_f}{W_f + W_{tank}} \tag{1}$$

where W_f is the fuel weight stored in the tank and W_{tank} is the weight of the tank itself. The gravimetric efficiency is used to calculated the fuel tank weight and this weight is added to the operating 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 tank to the remainder of the fuselage [28]. Storing fuel in the fuselage however also affects the wing weight as the bending moment alleviation effect of the fuel weight is no longer present. The magnitude of this increase is estimated using the inertia relief factor of the wing weight correlation from Ref. [21] using the method as explained in Ref. [12].

The design and integration of the hydrogen tank have a strong impact on the overall aircraft design and its energy use.

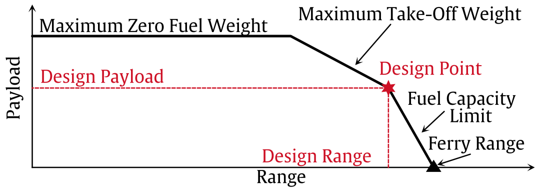

Fig. 1 – Payload-range diagram.