# AN ASSESSMENT OF THE POTENTIAL OF HYDROGEN FUELLED LARGE LONG-RANGE TRANSPORT AIRCRAFT

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## Abstract

*The rapid growth of air traffic prohibits the reduction of the absolute levels of $CO_2$ by aviation, despite the increasingly clear need to do so. Alternative fuels like hydrogen could therefore allow a sustainable growth of air traffic. However, the adoption of hydrogen as an aviation fuel poses several technical challenges and an assessment of its economic potential is thus in order. In this paper this assessment is made for a large long range transport aircraft.*

*After a brief description of the routine used to perform the preliminary design of both kerosene and hydrogen fuelled aircraft, a case study on a large long range transport aircraft is reported. For both fuels the wing area and aspect ratio leading to minimal direct operating costs are determined and the influence of the price level of the fuel is given. It is shown that hydrogen might have a significant economical potential as the fuel price for a given amount of energy can be twice as high for hydrogen without leading to an increase in operational costs.*

## 1 Introduction

Civil aviation faces a mounting conflict between the rapid growth of traffic demand and the increasingly clear need to reduce the emissions of greenhouse gases, particularly $CO_2$, into the atmosphere. Even though advances in aeronautical technology have lead and will lead to a significant improvement in the energy efficiency of transport aircraft, there is no realistic prospect that such gains in efficiency will be sufficient to compensate for the anticipated traffic growth as far as greenhouse gas emissions is concerned. Nor is it likely that aviation will be accorded a privileged exemption from the general need to reduce $CO_2$ emissions.

As an energy carrier which could be produced from any primary energy source - especially from renewables or nuclear energy as this would lead to a completely $CO_2$ free chain from "well to wing" - the adoption of hydrogen would protect sustainable long term growth of air traffic and also improve the reliability of the energy supply to the aviation sector. As multiple technologies can be used to produce the hydrogen fuel, a more stable price would normally be obtained as well. Increases in production costs through one specific technology could namely be counteracted by switching to another primary energy source. This would lead to a much more stable economical environment for the complete aviation sector, in big contrast with the current situation where airliners are facing the daily challenge of continuously rising kerosene fuel prices, a situation not likely to change in the future seen the dwindling resources of fossil fuels and the rising demand.

However, the use of hydrogen as an aviation fuel entails several technical challenges on the aircraft level. Even though hydrogen fuel contains, weight for weight, 2.8 times more energy than kerosene, a significant part of this advantage will be eaten up by the weight of the complex fuel system, specifically the large, bulky and heavy cryogenic fuel tanks. After all, to store the same amount of energy, liquid hydrogen needs a volume about 4 times bigger than kerosene. In addition, the tanks must be spherical or cylindrical in shape to allow for insulation requirements, which results in unusual aircraft configurations with the fuel tanks inside the fuselage.

This paper assesses the economical and operational potential of hydrogen for large long range transport aircraft. In a first section, the routine developed for the preliminary design of kerosene and hydrogen fuelled aircraft is briefly described, focussing on the adaptations needed when using hydrogen fuel. As the tanks are a critical component of the hydrogen fuelled aircraft, the next section is devoted to their design and sizing. Once all models used are established, a case study is run on a 380 passenger 7500 nm transport aircraft.

## 2 Description of the preliminary design routine for hydrogen fueled aircraft

As one of the main goals of this work is an assessment of the technical and economical potential of hydrogen fuelled long-range transport aircraft, in a first step a routine was developed for the preliminary design of kerosene fuelled aircraft. The structure of this routine is given in Fig. 1. As shown on the figure, input is required for the engine fuel consumption during the different flight phases and to define the mission range, initial cruising altitude, cruise Mach number and number of passengers. The diameter of the fuselage and the length of the cabin need to be given as well to set up a design calculation. Based on these input parameters, the different modules of the routine are called to perform the preliminary design calculations.

More details on the different modules and the adopted correlations for the calculations of the mass of the components, the drag and lift of the aircraft, the performance requirements and the direct operating cost calculations can be found in ref. [13] and [14] where some results for large long range passenger aircraft case studies are given too.

Here, only the changes in the method to allow the designs of the hydrogen fuelled aircraft

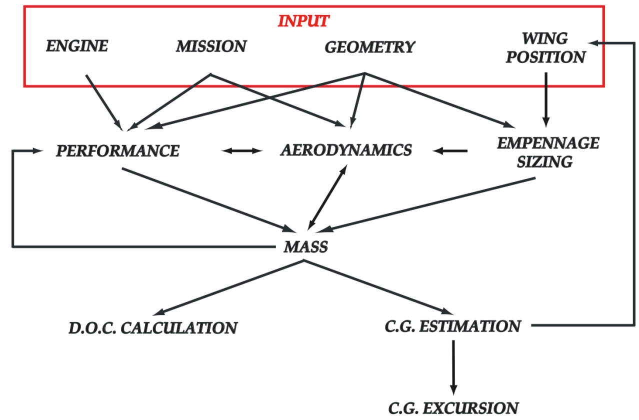


**Fig. 1** The structure of the routine

will be commented upon. As the hydrogen fuel will be stored in large tanks inside the fuselage, its weight and size need to be reassessed. The same applies to the wing as the wing root bending moment is no longer relieved by the weight of the fuel stored in it. As the hydrogen tanks might entail an increased aircraft acquisition and maintenance cost, the direct operating cost calculations are also reviewed.

### 2.1 Changes to the aircraft fuselage

The liquid hydrogen fuel has to be stored in tanks inside the fuselage (ref. [1], [3] and [9]), so both the geometry and the weight of the fuselage need to be adapted when changing from kerosene to hydrogen designs. As the fuselage length will depend on the amount of fuel needed for the mission, an iteration on the length is required.

The fuselage weight for the kerosene aircraft is calculated as the average of the weights obtained with the correlations from references [2] and [4]. Equation 1 gives the correlation from reference [2]:

$$W_{fus} = K_e K_{lg} S_{wet} \left( 10 + 1.2d + 0.0019 \frac{n W_{dim}}{h^{1.7}} \right) \quad (1)$$

where $d$ and $h$ are the fuselage diameter and height [$m$], $n$ is the ultimate load factor [–], $W_{dim}$ the fuselage dimensioning mass [$kg$] and $K_e$ and $K_{lg}$ correction factors for the engine respectively main landing gear location [–].

Both adopted correlations use the wetted area of the fuselage to determine its weight, so the effect of the increase in fuselage size is already implicitly included. However, the reinforcements needed to accomodate the tanks will increase the fuselage weight even more. According to ref. [3], this can be accounted for by an increase of the weight by 6%.

For longitudinal balancing and to ensure a proper location of the aircraft centre of gravity, two tanks are adopted in this design. One tank is positioned in the front section of the fuselage, in between cockpit and cabin. The second tank is located aft of the cabin in the tailcone of the aircraft. Following ref. [3], the front tank is taken slightly smaller than the aft tank, storing 40 % of the total fuel.

## 2.2 Changes to the aircraft wing

The cryogenic liquid hydrogen fuel is not stored in the wing, so its weight will not reduce the wing root bending moment as is the case with the kerosene fuel. The structural weight of the wing will therefore slightly increase, keeping all other influential parameters constant.

Some of the correlations for wing weight calculations found in literature take the effect of the fuel weight on the bending moment into account by a so-called bending relief factor. The correlations from references [2], [4] and [5] are adopted in this work as all three allow to take the absence of the fuel in the wing into account. The average of the 3 methods is used as the final wing weight.

## 2.3 Changes in direct operating costs

The change to hydrogen fuel represents a very significant one-time capital investment cost to adapt the complete infrastructure of all airports in the world. In this work, this cost of changing the infrastructure will not be considered to allow a comparison of kerosene and hydrogen fuelled aircraft on a fair and equal basis. Therefore only the direct operating costs will be used in the assessment.

Direct operating costs are those costs associated with flying the plane and its maintenance. They comprise the costs associated with the initial capital investment when buying the airplane (depreciation, insurrance), the cost of operating the plane (fuel, crew) as well as the maintenance cost. Direct operating costs are normally used in the preliminary design phase to identify the optimal size and configuration of the aircraft as they only consider the operational aspects of the total costs.

Apart from the hydrogen fuel storage and delivery system, the hydrogen fuelled aircraft are similar to their conventional kerosene-based counterparts. The main changes in aircraft direct operating costs will thus stem from the integration of the cryogenic fuel tanks in the aircraft. As it is hard to predict the influence of these tanks on the overall aircraft price, the acquisition and maintenance cost of the airframe (aircraft less engines) will be varied for the different case studies. An increase of 10,50 and 100 % of the airframe acquisition and maintenance cost is used to assess its influence on the overall direct operating cost as shown in the case studies of section 4.

# 3 Design of the $LH_2$ tanks

The design and development of the fuel tanks and their thermal protection systems to contain cryogenic liquid hydrogen in a satisfactory manner is regarded as one of the crucial technical challenges confronting use of $LH_2$ in operational aircraft (ref. [1], [3] and [9]). After all, this type of tank currently does not exist as cryogenic $LH_2$ tanks for space applications are designed for a very short tank lifetime and a limited number of cycles. Automotive applications are, on the other hand, much less influenced by weight limitations, which leads to relatively heavy designs that are not suited for aeronautical applications.

To minimize the weight of the tanks, integral tanks, where the tank wall forms a part of the basic airframe structure, are adopted. They namely lead to a lower tank weight and a smaller overall tank volume compared to non-integral tanks (ref. [1] and [3]). As the fuel is stored as a cryogenic liquid at roughly 20 K a good tank insulation is critical to the success of the tank design. Based on extensive studies by NASA and in the Cryoplane project (ref. [3] respectively [1]), two different families of insulations are adopted: a foam insulation and a multi-layer insulation. Foam insulations will namely be slightly thicker due to the lower thermal performance but they only require a single tank wall and are inherently cheaper than a multi-layer insulation. The latter consists out of alternating layers of double-aluminzed mylar reflective sheets and low conductivity spacer material, operated at vacuum level below 13 mPa (ref. [6], [7], [9] and [10]) and are therefore more expensive to build and maintain. The need for a vacuum operation furthermore entails an operational risk for the aircraft. A vacuum break would after all lead to a rapid boil-off of the liquid hydrogen. For the case study in this paper only foam insulations will be analysed.

During the flight the pressure inside the tank will fluctuate as a consequence of the fuel consumption of the engines and the boil-off of liquid due to the heat input in the tank. A minimum tank pressure, slightly above atmospheric pressure needs to be set to prevent air leaking into the tank. For safety reasons, a venting pressure also has to be set. In case of a degradation of the insulation, the tank pressure will namely rise significantly and a venting valve has to be foreseen for safety reasons. The value adopted for this venting pressure is a compromise between the tank wall weight and the insulation thickness and weight. After all, if a low venting pressure is set, a thick insulation will be required to limit the heat input in the tank.

The pressure variation for a homogeneous cryogenic tank can be calculated through an integration of the following formula (ref. [8]):

$$\frac{dP}{dt} = \frac{\phi}{V}\left\{Q - \dot{m}_{out}\cdot h_{lg}\left[x + \frac{\rho_g}{\rho_l - \rho_g}\right]\right\}$$

where $P$ is the pressure in the tank $[Pa]$, $t$ the time $[s]$, $Q$ the heat input in the tank $[W]$, $\dot{m}_{out}$ the fuel flow $[kg/s]$, $h_{lg}$ the heat of vaporization at the current pressure $[J/kg]$, x the quality of the two-phase mixture $[-]$, which is the ratio of vapour mass to liquid mass in the tank and $\rho_g$ and $\rho_l$ the density of the gas and liquid phase at the current pressure $[kg/m^3]$. The so-called energy derivative $\phi$ $([Pa/(J/m^3)])$ represents the pressure rise due to an energy input in a given volume for the two-phase mixture.

As some level of stratification will occur during the flight, a factor of 2 is added to the homogeneous pressure rise rate, following ref. [8]. The fluid convection due to the acceleration and vibration levels of the plane and the conductivity of the tank wall will namely result in a more or less homogeneously mixed tank so the level of stratification will be relatively small (ref. [1] and [3]).

Figures 2 and 3 show the influence of the venting pressure for the tanks of the aircraft under consideration. For each venting pressure the minimal insulation thickness to prevent venting during the flights is determined. As shown a significant variation in tank wall weight is obtained. Below the optimum, the tank weight increases due to the need of a thicker insulation, which furthermore leads to a slightly longer tank for a given mass of fuel as the outer diameter of the tank is set to the fuselage diameter. For venting pressures higher than the optimum pressure, the weight increases as the tank wall has to be designed for higher burst pressures.

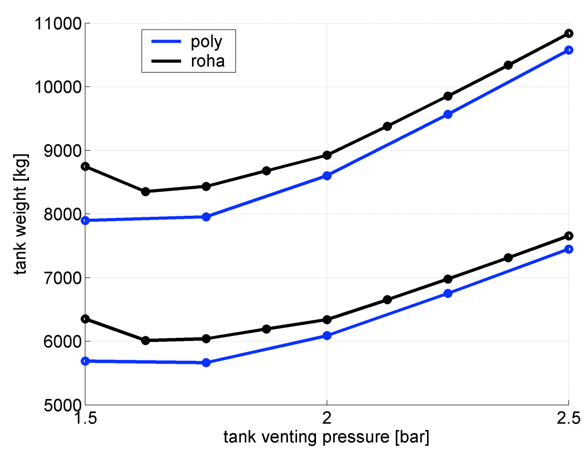


**Fig. 2** The weights of the two tanks for polyurethane and rohacell foam

The figures furthermore show that the vent-

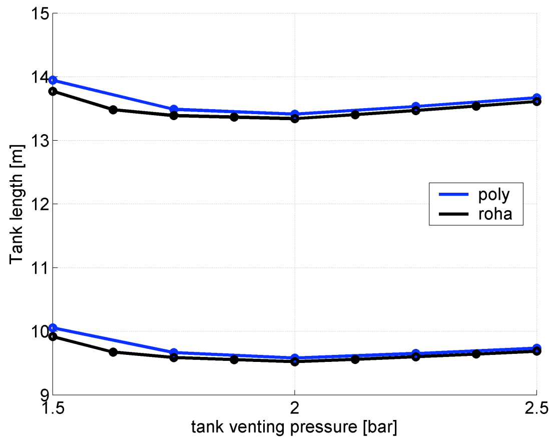


**Fig. 3** The length of the two tanks for polyurethane and rohacell foam

ing pressure leading to a minimal tank length is higher than the pressure leading to a mimimum weight (2 respectively 1.75 bar). As the change in tank length is relatively small for this particular applicaton, a venting pressure of 1.75 bar is used for the case study of this paper.

## 4 Case Study: 380 passengers long range transport aircraft

New passenger transport aircraft design studies are usually preceded by an extensive market study to determine the design mission for the aircraft. Usually a 'family' approach is adopted to mitigate the financial risks involved with the decision to start a new design and possible future stretch and shrink versions of the baseline fuselage are taken into account. As the market study is without the scope of this work, a typical single deck long range aircraft specification is adopted from ref. [11].

An aircraft housing 380 passengers in a three class layout with a design range of 7500 nm at Mach 0.84 is withheld for the case study under investigation. Besides the basic 3 class layout a stretched version carrying 454 passengers in the same 3 class layout and the respective single class high density version will also be considered in the design of the fuselage. The initial cruising altitude is set to 35000 ft and a stepped cruise with steps of 2000 ft is allowed. The reserve fuel is calculated using a diversion mission with a cruise range of 200 nm and a hold phase as shown on Figure 4

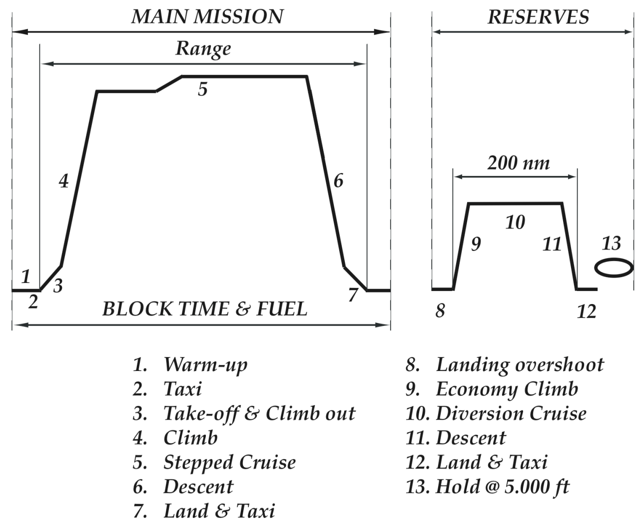


**Fig. 4** The mission profile for international flights

For the current study only a four engined version of the aircraft is considered. A turbofan with a BPR at take-off of around 8.4, similar to the GE90 is considered and its data is obtained with the Gasturb software. More data on the engine and its performance can be found in ref. [12].

Below, first the baseline kerosene version is determined. After sizing the fuselage a wing parametric study is performed to determine the aspect ratio and wing area that lead to minimal direct operating costs. Once the kerosene fuelled aircraft is sized, the hydrogen fuelled version is designed using a similar approach and the influence of the increased acquisition cost is assessed. In a final subsection, the direct operating costs for both fuels are compared.

### 4.1 Baseline kerosene version

For the kerosene version a single deck fuselage layout is adopted. For the range of passengers considered only a 3-4-3 seating arrangement is possible for the economy class. A 2-5-2 arrangement would namely lead to a stretch version that exceeds the 80 m airport constraint. With this

3-4-3 seating a diameter of 6.95 m is obtained for the cylindrical mid section of the fuselage. The corresponding first and business class seatings are 2-2-2 respectively 2-3-2. The baseline fuselage is 68.48 m long and can accomodate 550 passengers in the single class high density layout.

The wing area and aspect ratio have a significant impact on the aerodynamic efficiency of the aircraft and thus also on fuel consumption and direct operating costs. A wing parametric study to determine the optimum combination of both parameters is therefore executed using the direct operating costs of the aircraft as the figure of merit. Figure 5 shows the direct operating costs for different wing designs for a fuel price of 0.8 US$ per gallon. The wing area is varied between 300 and 450 $m^2$ whereas aspect ratios are taken between 8 and 12. The colours on the figure indicate contour levels of DOC. The black lines indicate approach speeds in knots while the full white line indicates the limit of volume available in the wing to store the fuel. On the left and above the full white line the wing is too small to store all the fuel. The white dashed line on the other hand shows a limit on the wing shape to avoid buffet onset during the flight (ref. [4]). Again the area to the left and above the line needs to be excluded from the design space.

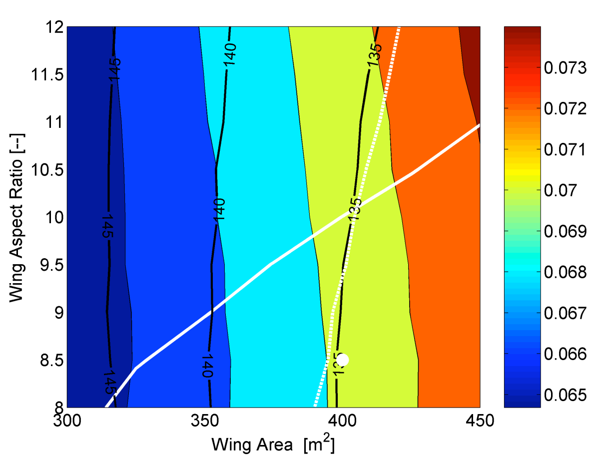


**Fig. 5** DOC per seat mile for 0.8 US$ / gallon

Based on the above mentioned limits, the final wing design point is selected:

$$S_w = 400m^2 \qquad AR_w = 8.5$$

This point is indicated by the white dot on Figure 5. Table 1 summarizes the most important characteristics of the airplane whereas figure 6 shows the fuel weight for the design mission under consideration.

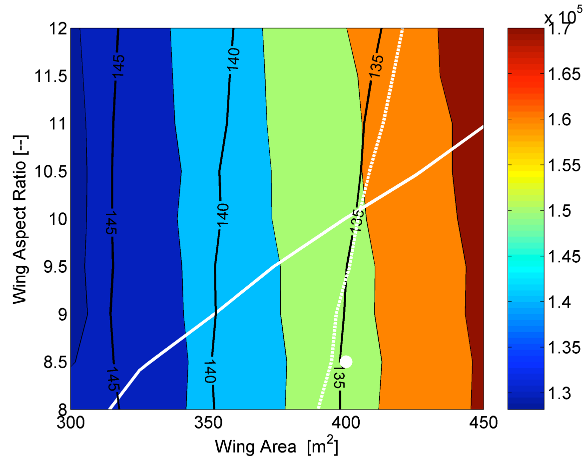


**Fig. 6** The fuel weight for the design mission $[kg]$

As the direct operating costs are used as the figure of merit an investigation on the influence of the adopted price level on the choice of the design point is in order. The fuel price for kerosene is varied from about 0.4 US$ / gallon to around 2.6 US$ / gallon to anticipate the rising kerosene prices. As shown on Figure 7 the assumed price for the fuel does not change the shapes of the direct operating costs considerably. It just alters the level of the total costs and the relative contribution from the fuel.

## 4.2 Baseline hydrogen version

To select the baseline hydrogen fuelled transport aircraft, a similar approach is used as for the kerosene fuelled version. However, seen the presence of the fuel tanks inside the aircraft fuselage, its size can no longer be fixed before setting up all calculations. After all, the total fuselage length will be determined by the size of the fuel tanks and thus by the amount of fuel to be stored for

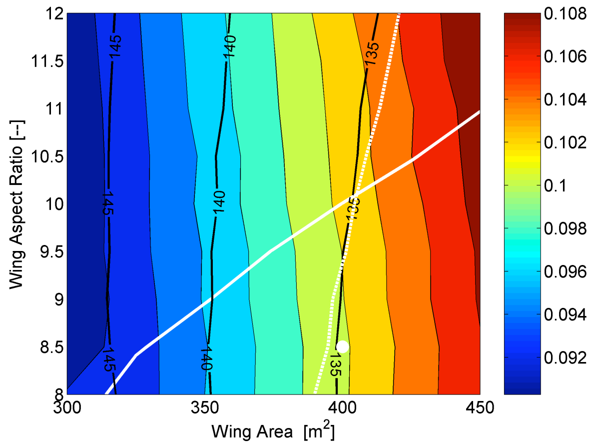


**Fig. 7** DOC per seat mile for 2.6 US$ per gallon

the mission. Instead of fixing the overall length once the cabin has been designed, one can only fix the cabin and the cockpit length. The fuselage length is then determined iteratively based on the size of the fuel tanks.

As the fuel tanks inside the fuselage will lead to a longer fuselage than for a kerosene fuelled aircraft, a double deck version has to be considered seen the requirement of a strech version. In the design under consideration, the upper deck houses all the business class passengers in the front of the deck. The first class is on the other hand situated directly below the business class on the lower deck of the fuselage as this will allow an easier embarking of first and business class passengers. The remaining part of both decks then houses the economy class passengers. Both first and business class have a 2-2-2 seating whereas the economy class seats are arranged in a 2-4-2 respectively 3-4-3 accomodation for the upper and lower deck. This leads to a fuselage diameter of 7.65 m and a fuselage length without tanks of 47.35 m (cabin, cockpit and part of tail cone)

As was also the case for the kerosene fueled aircraft, a wing parametric study is executed to fix the overall characteristics of the plane. The resulting direct operating costs of this parametric study are given on Fig. 8. Obviously, as the fuel is no longer stored in the wing, the wing size is no longer limited by a volume requirement so this line is omitted from the figure. All other lines have the same meaning as on Fig. 5. As shown in the caption of the figure, the fuel price is no longer given in US$ / gallon but in US$ / MJ instead. The values however correspond for a kerosene lower heating value of 43.1 $MJ/kg$.

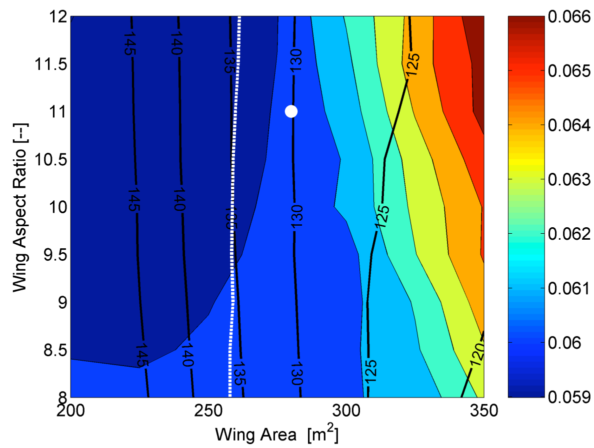


**Fig. 8** DOC per seat mile for 0.006 US$ / MJ

As can be seen from the figure, the following design point, indicated by a white spot has been chosen for the hydrogen baseline aircraft:

$$S_w = 280 m^2 \qquad AR_w = 11$$

A relatively big margin to the buffet limit from ref. [4] has been adopted. After all, the fuel in the wing acts as a damper on the aerodynamically excited vibrations, so its absence will lead to a higher susceptibility of the wing to flutter. In a later stage of the work, more detailed calculations will be made to substantiate the adopted margin. Table 1 summarizes the design point data for the hydrogen fuelled aircraft. The direct operating costs are given for the same price per energy content of the fuel as for the kerosene fuelled aircraft.

As shown in the table, the liquid hydrogen fuelled aircraft has more or less the same operating empty and landing weight as its kerosene counterpart, despite the much smaller wing area. However, the low fuel load leads to a much lower take-off weight for the aircraft. The wing of the

**Table 1** Design point for kerosene and hydrogen fuelled aircraft

| | | |
|---|---|---|
| $S_w$ $[m^2]$ | 400 | 280 |
| $AR_w$ $[--]$ | 8.5 | 11.0 |
| $W_{TO}$ $[kg]$ | 320760 | 205280 |
| $W_F$ $[kg]$ | 156110 | 40240 |
| $W_{OE}$ $[kg]$ | 128450 | 128840 |
| $W_L$ $[kg]$ | 172820 | 167720 |
| $DOC$ [US$ c /pax/nm] | 7.03 | 6.01 |

hydrogen fuelled aircraft also has a higher aspect ratio than for kerosene fuel.

### 4.3 Influence of an increased aircraft acquisition and maintenance cost

As indicated previously, the change in the fuel storage and delivery system might change the cost of acquisition and maintenance for the hydrogen-fuelled aircraft and possibly also the wing size and aspect ratio leading to the minimal direct operating cost. Figures 9 and 10 show the DOC contours for an increase in acquisition and maintenance cost of 50 respectively 100 % .

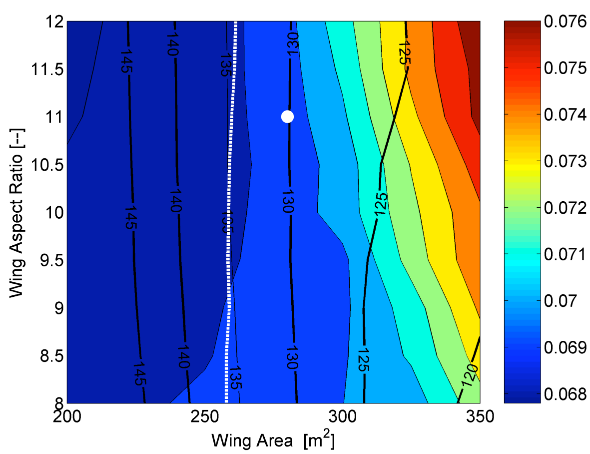


**Fig. 9** DOC per seat mile for a 50 % increase in acquisition and maintenance cost

The figures show that the shape of the contour lines remains more or less the same up to 50% increased cost. At a 100 % higher acquisition and maintenance cost, the contour lines are however slightly different due to the increased importance of the aircraft takeoff gross weight on the DOC. However, it seems to be highly unlikely that the change in the fuel delivery and storage system would entail the doubling of the price of the aircraft.

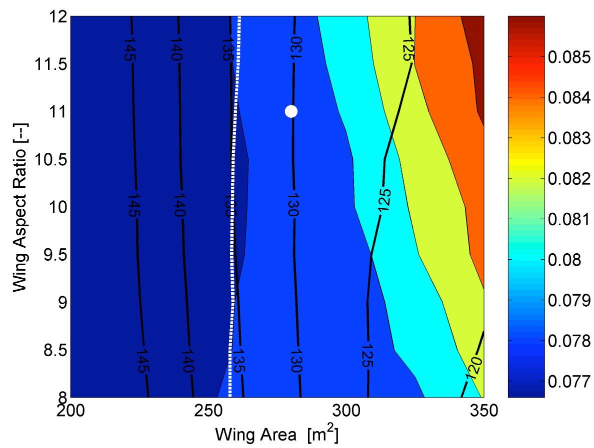


**Fig. 10** DOC per seat mile for a 100 % increase in acquisition and maintenance cost

### 4.4 Equivalent hydrogen price for same mission direct operating costs

To allow a correct assessment of the economic potential of hydrogen fuelled large long range transport aircraft, the price of both fuels is varied and the resulting direct operating costs are calculated. As indicated previously, the optimal point is not affected by the value assumed for the fuel price. All calculations can thus be done for a single wing design. For each fuel, the optimum previously determined is adopted. Figure 11 gives the results of this calculation.

The figure clearly shows that a significantly higher price can be paid for the hydrogen fuel, based on the amount of energy stored. At a price of about 80 cents per gallon of kerosene (0.006 $/MJ) the price of hydrogen can be almost twice the kerosene price to obtain similar direct operating costs. If a 50 % increase in acquisition cost is assumed the price of hydrogen can still be about 10% higher. As the curves diverge, the extra money that can be paid for the hydrogen fuel

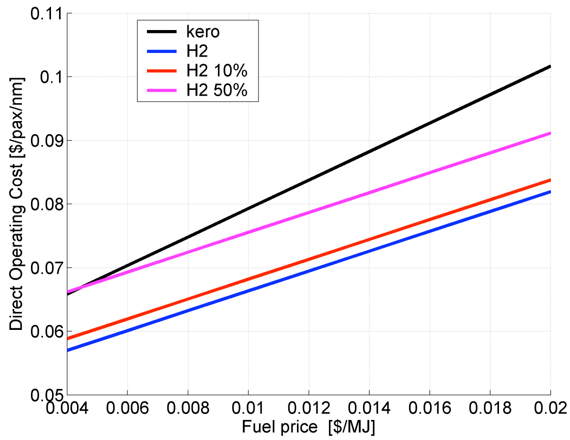


**Fig. 11** Comparison of DOC for different fuel prices

(based on an equal amount of energy) increases for increasing kerosene prices. This shows that the potential of hydrogen will increase with time.

## 5 Conclusion and future work

Seen the increasing attention paid to the emissions of greenhouse gases into the atmosphere, alternative fuels like hydrogen which could provide a $CO_2$ free flight become more and more interesting. However, the change to hydrogen as an aircraft fuel poses several technical challenges and its performance and economical potential needs to be assessed.

After a brief description of the routine used to perform the preliminary design of both kerosene and hydrogen fuelled aircraft, a case study on a large long range transport aircraft is reported. For both fuels the wing area and aspect ratio leading to minimal direct operating costs are determined and the influence of the price level of the fuel is given. It is shown that hydrogen might have a significant economical potential as the fuel price for a given amount of energy can be twice as high for hydrogen without leading to an increase in operational costs.

As only conventional engines are used for the case study under investigation, the potential of hydrogen might even be bigger than shown here. After all, the heat sink of the cryogenically stored fuel can be exploited to reduce the fuel consumption of the engines. In the future, unconventional engines using heat exchangers will therefor be simulated.

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