FEASIBILITY STUDY OF MODIFYING A BASELINE KEROSENE AIRCRAFT TO A LH2 POWERED VERSION

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Abstract

The main aim of this paper is to investigate the feasibility of conceptually modifying an existing kerosene aircraft to a LH2 powered version which is capable to fulfill the route between London and New York with a stop at Iceland. The reason for choosing this rout is that the LH2 versions could be refueled at Iceland where abundant geothermal energy could be utilized for producing electricity, which could be used for generating LH2 by electrolysis of water. This paper aims to find out which modified version is more economic for this route, the modified version with inevitable modifications or the modified version with relatively more modifications?

1 Background

During the last decades, the global revenue passenger kilometer (RPK) of the air transportation has doubled every fifteen years, and this trend is estimated to continue for the following decades [1]. Inevitably, this growing air transportation will cause more greenhouse gas which is one of the main causes of global warming. Even if the fuel efficiency of kerosene improves 2% annually, it is estimated that world aviation emissions several years later would be almost doubled. If this trend maintains for decades, emissions could grow up to 3-7 times further in the middle of this century [2]. Greenhouse poses a great threat to people's health, and it is estimated that each year about 150,000 people lose their lives due to the climate change caused by greenhouse gas [3]. Hence, it is becoming increasingly urgent and important to reduce the air traffic impact on the climate change. A very promising way to reduce the greenhouse emissions is to burn some alternative fuels like liquid hydrogen (LH2) compared to burn traditional hydrogen-carbon fuel [4].

The main aim of this paper is to investigate the feasibility of modifying a kerosene aircraft to a LH2 powered aircraft. The aimed flying route is between London and New York, with a stop at Iceland where the modified versions would be refueled with LH2. There are two reasons for choosing this route between London and New York. One is that this route has a big passenger volume and it is one of the busiest international routes. The other reason is that the modified versions could be refueled in Iceland where abundant geothermal energy could be utilized for producing LH2 by electrolysis of water.

2 Requirements and Market Forecasts

2.1 Range

In terms of range design requirement for the Iceland mission, the flying route is between London and New York, and distances measured are shown in Figure 1

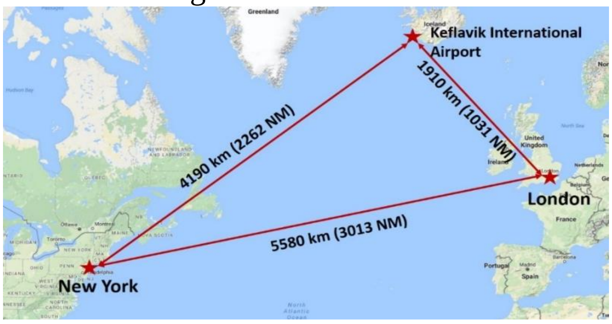

Fig. 1. Flying Routes And Distances

Since the kerosene fuelled version and LH_2 fuelled version burns different fuel, the flying trips of Iceland mission for two versions are different to some extent, and their missions are analyzed in the following (Results see table 1):

- Kerosene fuelled version: Take-off from New York, kerosene fuel is added → Landing at London, kerosene fuel is added, take-off from London → Landing at New York, kerosene fuel is added.
- LH2 fuelled version: Take-off from Iceland, LH2 fuel is added → Landing at New York, take-off from New York, no fuel is added → Landing at Iceland, take-off from Iceland, LH2 fuel is added → Landing at London, take-off from London, no fuel is added → Landing at Iceland, LH2 is added.

Table 1 Summary of Range Requirements

Version	Longest Distance	Range
Kerosene	5580 km (London ↔ New York)	5580 km
LH_2	4190 ×2=8380 km (Iceland → New York → Iceland)	8380 km

2.2 Seat Capacity

Normally, there are two different ways to determine the seating capacity. One is to draw a plot or a figure between the range capability and number of seats for current aircraft [5]. The other way is to investigate the airliners which are currently under service. For modification designs, however, the airliners operators might want to modify a current aircraft (like B787-8) to a LH2 fuel version, since it reduces the development cost and minimizes the technology risk. That means only inevitable changes may be applied, leaving the fuselage, wing and other major components unchanged. Inevitable changes include removing some seats away to accommodate the LH2 fuel tank, modifying a kerosene powered engine to a LH2 powered engine, and adding necessary LH2 fuel system to replace the kerosene fuel system. Therefore, the fuselage will be maintained unchanged during the modification design, and some lines of seats have to be moved away to accommodate the LH2 fuel tank, so the seating capacity turns out to be an output of the modification design rather than an initial input data for modification. It would be a trade-off result between fuel tank volume and seat capacity, a result of maximum seat capacity and with minimum fuel tank volume which could store required amount of LH2 to cover the required range.

2.3 Speed

One important design requirement is the cruise speed, which is normally required by the airliner operators. For the purpose of this study, it could be figured out by referring to similar aircraft. Hence, a plot for cruise speed against range was plotted [6]. As can be seen in Figure 2.

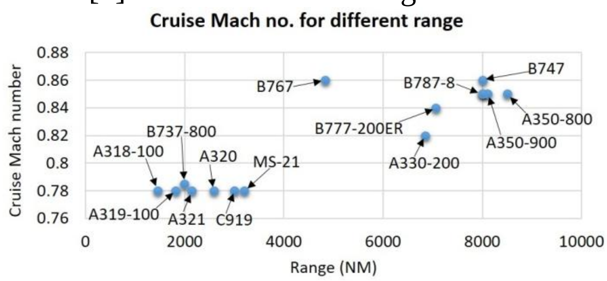

Fig. 2. Cruise Mach No. Versus Range

It can be seen in Figure 2 that for a domestic aircraft, the cruise speed is around M0.78, while for international civil aircraft the cruise speed varies from 0.82 to 0.86. For the purpose of this thesis, considering that it is utilized for an international route, so a typical cruise speed of M0.85 was chosen for this thesis. And this cruise speed is in accordance with the cruise speed of B787-8. For the maximum speed, a value of M0.9 was decided for this thesis.

2.4 Runway Length

In terms of the runway length, considering that modification designs were similar to B787-8, so the same requirements were utilized for the modified versions. The maximum certificated runway for MTOM at take-off under ISA sea level conditions should not exceed 2900m, and the factored landing distance at maximum landing mass at ISA sea level conditions should be no more than 1750m.

2.5 Summary of Requirements

According to the analysis above in this chapter, key design requirements are summarized and listed as follows:

- Seat capacity (Unchanged fuselage): An output result of conceptual design.
- Range for kerosene version: 5580 km (3013 NM).
- Range for LH2 version: 8380km (equals to 4524 NM).
- Cruise speed: Mach 0.85.
- Maximum speed: Mach 0.90.
- Take-off field length:≤2900 meters.
- Landing field length:≤1750 meters.

2.6 Sales Projection

In terms of sales projection of a new airliner similar to B787-8, considering that it is a newly developed concept which belongs to the wide-body class, so it could be assumed that it can occupy about 20% of the wide-body aircraft market, with competitors like A350 and B787. The sales projection could be figured out once the overall wide-body sales projection is figured out. The trend of the total sales volume is shown in the left part of Figure 3, and the projected sales number by the formula is shown in the right part of Figure 3.

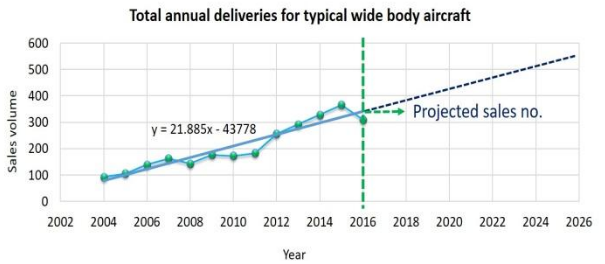

Fig. 3. Sales No. For Wide-Body Aircraft

The service entry year of this new concept aircraft is around 2025, according to Figure 3, it is projected that the 20-years (2025-2044) total sales amount of wide-body aircraft turns out to be 14940, and the 20-years sales projection of this new concept airliner is calculated to be 2988 (occupies 20% of the wide-body market). Hence, the production rate is 12 aircraft per month. And this data was utilized as input data for acquisition cost.

3 Conceptual Design Methodology

3.1 Design Approach

The study of this paper is based on the spreadsheet of conceptual design modules. Eleven modules are included in this spreadsheet, they are International Standard Atmosphere (ISA) module, geometry module, mass module, centre of gravity (c.g) module, propulsion module, aerodynamic module, performance module, stability module, acquisition cost module, direct operating cost (DOC) module, and emission module namely.

The conceptual design approach is illustrated in Figure 4.

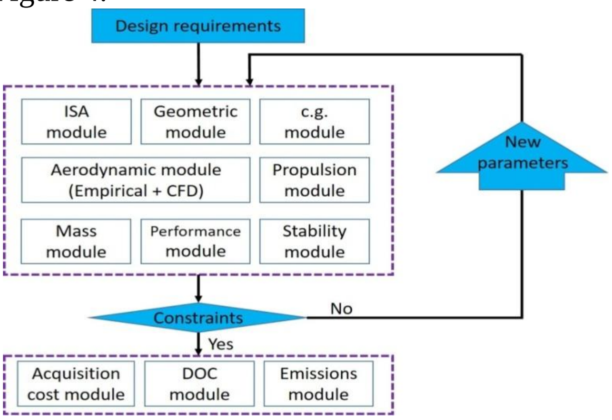

Fig. 4. Conceptual Design Approach

3.2 ISA Atmospheric Module

Since some parameters including density and sonic speed are needed for calculating the cruise performance and field performance, the ISA atmosphere model was generated in the spreadsheet based on ESDU method [7]. The ISA atmosphere is divided into seven layers for altitudes up to H=80km [7]. Considering that the civil aircraft mostly cruise at an altitude range from 10500 to 13000 meters [6], so it mainly falls into the Troposphere and stratosphere layers.

3.3 Geometry Module

Geometry model is of great importance and it offers input data for the mass model, aerodynamic model, and stability model. The parameter definitions of wing, tail, and fuselage are defined by referring to Jenkinson [8]. These geometric equations are general equations, which mean that they are suitable for all civil aircraft with conventional configurations.

3.4 Mass Module

Two methods were used to calculate mass. The first method is mainly based on Cranfield AVD lecture notes [9] [10].The second is based on the book by Howe [11]. The AVD lecture note method was utilized as the basis for mass calculation. However, the Howe method tends to produce more reliable results for wing, fuselage, and empennages than the AVD lecture note method. So Howe method was utilized for mass prediction of wing, fuselage, and empennages. Key points are listed below:

- A combination of Howe method and AVD lecture notes method was used for mass module.
- Howe method was used for predicting the wing, fuselage, tail unit, crew mass, operating items, and payload of passengers.
- The AVD lecture notes method was used for predicting all other mass items except those by Howe method.
- A technology reduction factor of 0.9 was used for wing, fuselage, HT, and VT, to take the new material into account.

3.5 Centre of Gravity Module

Once the mass predictions have been performed, it is necessary to determine individual component c.g.. So that the overall c.g. and moment of inertia can be determined. For this paper, considering the AVD lecture note method is relatively more detailed compared to the Stanford method [12][13]. Hence, the AVD lecture notes method for c.g. was applied for the centre of gravity module.

3.6 Propulsion System Module

Although performance data of similar engines like Trent 1000A and Trent XWB-75 are available [14][15], the cruise thrust needed to be calculated based on the sea-level static thrust (SLST), and a smaller engine might need to be scaled based on these engines, detailed equations refer to Raymer and Howe [16][11].

3.7 Aerodynamic Module

With the input data from the geometric module, the aerodynamics are calculated in the aerodynamic module, and provides input lift and drag data for performance calculation, including cruise performance and field performance. Aerodynamic data of low speed from sea level to 1500 ft (for field performance) and L/D ratio at cruise speed were calculated. The Howe method [11] based on empirical equations is utilized.

3.8 Performance Module

Performance module has various input data including geometric data, aerodynamic data, mass data, engine data and design requirements. Field performance was calculated, including take-off field length, initial climb performance for one engine inoperative (OEI), and landing performance. Flight path performance was calculated. The Howe method for predicting field performance was used for conceptual design in this thesis. Besides, the Howe method was also applied for the initial climb performance [16]. For the cruise performance, the Breguet equations was applied for performance module.

3.9 Stability Module

The pitching moment plays an important role in the determination of static stability, it is possible to develop a simple approximation, which is sufficiently representative for conceptual design studies, and it could produce considerably reasonable results for the basic requirements for static stability and trim ability. One such method is used referred to Michael[17].

3.10 Acquisition Cost Module

The acquisition cost module was utilized for predicting the aircraft list price (ALP). ALP could be estimated by using detailed equations of predicting both the development cost and production cost. The burns method was utilized in this paper [18].

3.11 Direct Operating Cost Module

Operating cost incurred during the life cycle needs to be taken into account since it is normally much more than the development and production costs [16]. One of the indicators that can well express the aircraft operating cost is "Operating Cost Per Available Seat Mile" [19]. The NASA "DOC+I" method was selected and used for DOC module [20]. The fuel price for kerosene is 116.6 $ /barrel, 3$/kg for LH2 fuel.

3.12 Emission Module

At conceptual design stage, it is necessary to consider the emission pollution. The aircraft emissions are divided into two parts, the one occurred below 3000ft is called the landing and take-off cycle (LTO). The other one, which is above 3000ft, is for cruise phase [21]. Emission module for kerosene aircraft was based on IPCC (2006)[21], while emission module for LH2 version was based on Kolja, S. (2010) [22].

3.13 Module Modifications from Kerosene to LH2 Fuelled Aircraft

Since modified versions are fuelled by LH2, necessary modifications for the conceptual design modules need to be made to ensure these modules are suitable for designing a LH2 aircraft. There are substantial property differences between kerosene and LH2, and these property differences will have direct effects on aircraft design. These effects refers to Brewer [23]. Some modifications are made to modify the conceptual design model to make it suitable for a LH2 fuelled aircraft. These modifications are summarized in Table 2.

Table 2 Modifications for a LH_2 fuelled aircraft

Aspects	**Design model modification for LH_2 fuelled aircraft**
SFC	Factored with 1/2.9
More tank volume	Bigger and maybe heavier fuselage (or wing) Bigger wetted area Less L/D, depends on calculation
Fuel system weight	1.2 times of that of kerosene aircraft
Fuel tankage weight	Much heavier tankage, depends on calculation
MTOM	Lighter MTOM, depends on calculation
Engine weight	Smaller engine and lighter engine, depends on thrust requirement

4 Conceptual Design of the Baseline Kerosene Aircraft

With the given design requirements, the baseline kerosene fuelled version which is similar to B787-8 was designed by using the conceptual design modules. The configuration layout and cabin layout of baseline kerosene fuelled version are illustrated in Figure 5.

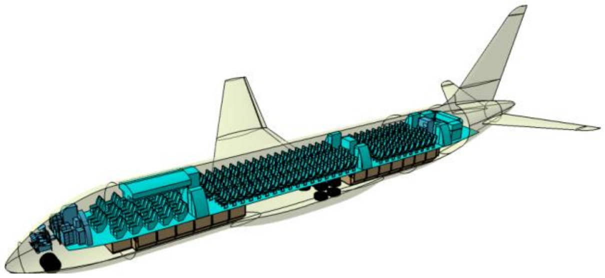

Fig. 5. Configuration And Cabin Layout For The Baseline Kerosene Version

The following modification designs are based on this baseline kerosene version. And the comparisons are conducted between the modification versions and this baseline kerosene version. Specification data for baseline kerosene version see table 3.

Table 3 Specification Data for Baseline Kerosene Version

Items	**Value**	**Items**	**Value**
No. of Passengers (2-class)	296	Span of HT (m)	21.779
Wing Span (m)	51.9	Span of VT (m)	8.596
Wing Area (m^2)	365.98	Fuel Mass (kg)	36952
1/4 Sweep Angle (deg)	32.2	Crew Mass (kg)	950
Fuselage Diameter (m)	5.85	Operating Items (kg)	3770
Fuselage Length (m)	56.81	Mass of Payload (kg)	28120

Horizontal Tail Area (m^2)	90.348	Operating Empty Weight (kg)	103835
Vertical Tail Area (m^2)	41.988	Take off Mass (kg)	169288

5 Modification Design with Minimum Changes

Once the baseline kerosene fuelled version was designed, the next issue needs to be set is to decide the position of LH2 fuel tank. According to the previous study, it shows that it would be more suitable to store the LH2 fuel tank in the fuselage rather than the wing [23][24]. Hence, for this modifications design, the LH2 fuel tank were initially placed in the fuselage, and a detailed LH2 fuel tank design for baseline kerosene version aimed at Iceland mission had been carried out by a previous study named ARTURO [24]. Two fuel tanks were stored in the fuselage, one LH2 tank was located in the AFT fuselage, and the other one was located in the FWD fuselage.

Based on previous fuel tank study, a detailed conceptual design work was performed by using the conceptual design methodology. The geometry of modified versions was left unchanged, several lines of seats were removed in order to place the bulky LH2 fuel tanks. The no. of lines of seats removed is 13, and it is a design output based on a rough calculation. In order to carry out a detailed conceptual design of LH2 version, a removed seat line number of 13 was utilized as an initial input data for conceptual design. For the modification design from baseline kerosene version to LH2 fuelled version, inevitable changes involved in the conceptual design modules are summarized and listed below:

- The weight of seals for kerosene tankage was removed away.
- 13 Lines of seats were removed, fewer passengers, less payload, fewer crew, less furnishing weight.
- LH_2 fuel tanks were installed, extra weight for LH_2 fuel tanks were added.
- Fuel system weight was factored with 1.2.
- SFC was reduced by a factor of 1/2.9.
- Less fuel weight due to the lower density of LH_2.
- Lower MTOM mainly due to the lighter fuel weight and fewer passengers.
- It was assumed that the fuselage structure weight of LH_2 version was the same as the baseline kerosene version.

Based on the conceptual design work, a more detailed cabin layout sizing work was conducted, and the available cabin space was extensively explored. The overall seat number turns out to be 184 seats (28 business seats, 156 economic seats). Figure 6 shows the configuration layout and the cabin layout of the LH2 version.

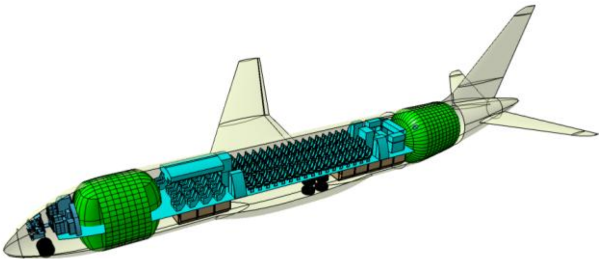

Fig. 6. Configuration Layout And Cabin Layout For LH2 Version

Specification Data for LH2 version with inevitable changes could be seen in table 4.

Table 4 Specification Data for LH2 version with inevitable changes

Items	Value	Items	Value
No. of Passengers (2-class)	184	Span of HT (m)	21.779
Wing Span (m)	51.9	Span of VT (m)	8.596
Wing Area (m^2)	365.98	Fuel Mass (kg)	18083.34
1/4 Sweep Angle (deg)	32.2	Crew Mass (kg)	850.0
Fuselage Diameter (m)	5.85	Operating Items (kg)	2220
Fuselage Length (m)	56.81	Mass of Payload (kg)	17480
Horizontal Tail Area (m^2)	90.348	Operating Empty Weight (kg)	103428
Vertical Tail Area (m^2)	41.988	Take off Mass (kg)	139086.34

6 Modification Design with More Changes

The baseline kerosene version is based on minimum changes which possibly required by most airliners operators, while other airliners operators might want to perform extensive modifications rather than minimum changes. Hence, further modifications were made for this loop design. These modifications include:

- The W/S was designed to be 5700 N/m^2, a smaller wing was utilized, and a smaller tail was utilized to maintain the same tail volume.
- The T/W was designed to be 0.305, a smaller engine was utilized.
- Winglets were added, L/D ratio increased by 7%, and the wing structure weight increased by 1.62% of the total wing structure weight.
- The average wing thickness was designed to be 0.1.
- Cruise L/D ratio was recalculated.
- Less fuselage weight due to integral fuel tank.
- Less fuel needed, LH_2 fuel tank weight reduced, and more seats were added, more furnishing weight.
- Reduced MTOM resulted in further reduced wing weight, system weight, smaller landing gear, and reduced weight for other components.

The fuselage was left unchanged, the seating number of LH2 version with relatively more changes would still be a trade-off result between LH2 fuel tank and seat capacity. Considering that the first loop design has 13 lines of seats removed, so seat line no. from 7~13 were investigated, the available fuel tank volumes were measured from the CATIA models. Results show that the minimum number of removed seat line turns out to be 8. In this case, the LH2 version with relatively more changes achieves its maximum passenger number. With these modifications, the LH2 version with relatively more changes was designed. Figure 7 shows the configuration layout and the cabin layout of the LH2 version with relatively more changes.

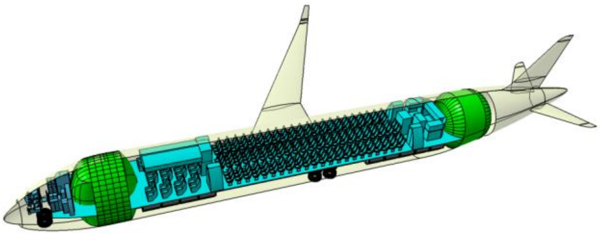

Fig. 7. Configuration And Cabin Layout For LH2 Version With Relatively More Changes

Specification Data for LH2 version with more changes could be seen in table 5.

Table 5 Specification Data for LH2 version with more changes

Items	Value	Items	Value
No. of Passengers (2-class)	229	Span of HT (m)	12.264
Wing Span (m)	44.135	Span of VT (m)	5.627
Wing Area (m^2)	184.38	Fuel Mass (kg)	12354.37
1/4 Sweep Angle (deg)	32.2	Crew Mass (kg)	680.00
Fuselage Diameter (m)	5.85	Operating Items (kg)	2748.00
Fuselage Length (m)	56.81	Mass of Payload (kg)	21755.00
Horizontal Tail Area (m^2)	28.650	Operating Empty Weight (kg)	73060.64
Vertical Tail Area (m^2)	17.988	Take off Mass (kg)	107170.01

7 Comparisons and Conclusions

Comparisons between baseline kerosene version and two different LH2 versions were studied in several aspects, such as aerodynamics, performance, acquisition cost (AC), DOC and emissions.

Table 6 Comparisons for three different versions

	Baseline kerosene version	LH_2 version (minimum changes)	LH_2 version (more changes)
Fuel	kerosene	LH2	LH2
No. of Passengers	296	184	229

Unstick C_L	1.422	1.422	1.4216
L/D at Cruise	14.88	13.58	16.18
C_L for Landing	1.706	1.706	1.706
Take-off Field Length (m)	1519	1067	2454
Accelerate stop length (m)	1484	1045	2356
2nd Seg. Climb Gradient Rate (OEI)	7.07%	10.96%	3.03%
Landing Field Length (m)	1389	1250	1586
Aircraft List Price (M$)	218.27	217.16	165.1
DOC Per ASM (CASM)	9.644	19.48	12.45
Total $\mathbf{CO_2}$ (kg) (A single trip)	106489	0	0

From the above table, it coul be concluded:

- In terms of the aerodynamics, the difference for unstick CL and landing CL for three versions are marginal, this is because three versions used almost the same wing and high-lift devices. while for the L/D ratio at cruise stage, the value for the LH2 version with more changes is much higher than those of other two versions, the reason is that the W/S for the LH2 version with more changes is more reasonable than those of other two versions, which means it can achieve a better L/D ratio at a given cruise altitude.
- In terms of performance, the baseline kerosene version shows shorter take-off field length and landing field length, this is because the baseline kerosene version has a higher T/W and lower W/S value.
- For the acquisition cost, it could be seen that the AC of LH2 version with minimum changes is slightly higher than that of the baseline kerosene version, this is due to a slight higher structure cost for LH2 version. The LH2 version with more changes has the lowest AC, the reason is that this modification version has a much lower structure cost and engine cost.
- For the DOC, it could be seen that the LH2 version with minimum changes is much higher than that of the baseline kerosene version, this is due to a considerably less passengers, fuel price. The LH2 version with more changes are much lower than that of the LH2 version with inevitable changes, the reason is that the Latter one could accommodate more passengers, a much higher L/D ratio at cruise, and a much lower acquisition cost.
- For the emissions, two modified versions produce no CO2 compared to the baseline kerosene version.

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