

Clean Hydrogen Energy Supporting Green Civil Aviation Development

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Abstract. Booming aviation and worsening ecology make aircraft emission reduction a key civil aviation research focus. Different from fossil jet fuels, hydrogen is a zero-carbon clean energy to cut carbon pollution. Optimized fuselage hydrogen tank layout reduces aircraft empty weight and lifts airline long-term profits, with balanced strengths in safety and cost control. Building on hydrogen's outstanding zero-carbon superiority over fossil jet fuels, this paper carries out integrated qualitative analysis and quantitative data research. Quantitative fuel thermophysical comparisons reveal hydrogen delivers triple the mass heating value but suffers from extremely low liquid density that restricts onboard storage. Two typical fuselage hydrogen tank layouts, together with passenger loss calculation formulas, are constructed to quantify cabin space occupation caused by cryogenic vessels. Five mainstream hydrogen storage tank types are qualitatively sorted by structural features, and hydrogen's long-term economic merits as well as latent aviation safety risks are comprehensively evaluated. The final research results fully confirm hydrogen's great practical aviation application potential and provide reliable parametric references for the conceptual design and sustainable industrial development of hydrogen-powered civil aviation.

Keywords: Hydrogen Aircraft, Liquid Hydrogen Storage Tank, Low Climatic Impact, Aviation Decarbonization

1. Introduction

The past 50 years have witnessed the rapid advancement of the global aviation industry. According to IATA's 2024 statistical data on global flight volume between 2004 and 2024, global air travel demand remains persistently high [1]. Flight numbers grew steadily before 2020, dropped temporarily amid the pandemic, and then recovered rapidly, verifying the enormous long-term market demand for civil aviation services.

Air transport brings convenience to human society, yet it produces substantial air pollutants. Human air travel creates 2.4% of total CO₂ from human activities, accounting for 12% of transport carbon and 4% of man-made global warming [2, 3]. Rising atmospheric CO₂ triggers global warming and sea-level rise, causing widespread environmental harm. Accordingly, this paper explores low-carbon aircraft design, with zero-emission hydrogen aircraft identified as a key development route.

Numerical studies have confirmed hydrogen aviation's strengths and limitations. Yusaf et al. built a full-life carbon model for medium-range aircraft and found hydrogen reduces carbon emissions by 98% [4]. Nemitallah et al. verified hydrogen's triple heating value versus Jet-A via thermodynamic fuel comparison [5]. Palaia et al. added that liquid hydrogen tanks take up an extra 18%–25% of fuselage space and limit cabin layout through fuselage parametric modeling [6].

The research first explains the working principles of hydrogen-powered aircraft and their advantages over traditional fuels. Design differences between hydrogen aircraft and conventional planes are further compared in this study. Safety and cost features of hydrogen storage technologies are finally discussed. All the above analyses are used to prove that hydrogen-fueled aircraft can play a key role in slowing environmental damage and achieving sustainable aviation development.

2. Hydrogen as an alternative fuel

One of the main concerns is how to reduce carbon emissions while reducing costs. This is significant because traditional fuels such as petroleum have low energy efficiency and cause serious environmental damage. Hydrogen aircraft are predicted to be the least expensive and most sustainable way to fly without carbon [7]. Among all available technical routes to cut aviation carbon emissions, hydrogen propulsion offers the cheapest carbon abatement cost per ton of CO₂, according to Airbus. With hydrogen's outstanding specific energy, aircraft running on hydrogen fuel can achieve lighter weight, lower energy consumption and reduced operation costs when adopting positive forecasting parameters.

Table 1. Fuel thermophysical and combustion properties [5]

Parameter	Unit	CH4	Jet-A	JP-4	Hydrogen
Gross Mass Combustion Enthalpy	kJ·kg ⁻¹	50	42.8	42.8	120
molecular weight		16	168	132	2
Laminar Flame Speed in NTP Air	m·s ⁻¹	2.65: 3.25	0.37: 0.45	0.4: 0.5	0.4: 0.6
Minimum Ignition Energy (MIE) in Air	mJ	0.29	0.25	0.25	0.02
heat capacity	J·g ⁻¹ ·K ⁻¹	3.50	1.98	2.04	9.69
diffusion velocity in NTP air	m/s	≤0.51	<0.17	<0.17	≤2.0
Normal Boiling Point (1 atm)	K	112	440: 539	333: 519	20.3
Latent Heat of Vaporization	J·g ⁻¹	510	360	344	446
Flammability Range in Air	%volume	5.3: 15	0.6: 4.7	0.8: 5.8	4 to 75
Autoignition Temperature	K	813	>500	>500	858
Adiabatic Flame Temperature at Stoichiometric Ratio (Φ=1)	K	2148	2200	2200	2318
Saturated Liquid Density	kg·m ⁻³	423	811	774	71

Table 1 presents obvious differences in physical and combustion properties among methane, Jet-A, JP-4, and hydrogen. Jet-A and JP-4 have an identical combustion heat of 42.8 kJ/kg, and methane reaches 50 kJ/kg. The liquid densities of the three fuels stand at 811, 774, and 423 kg/m³ separately, all much larger than liquid hydrogen at 71 kg/m³ [5]. Hydrogen achieves a mass combustion heat of 120 kJ/kg, which is three times that of aviation kerosene and twice that of methane. This feature brings prominent lightweight and long-distance flight advantages for large-load long-haul aircraft.

Nevertheless, hydrogen only has one quarter of Jet-A's volumetric energy density, which brings prominent difficulties to onboard storage. Such a huge density difference demands large-sized

cryogenic hydrogen tanks and supporting thermal insulation structures. In contrast, methane, Jet-A, and JP-4 can be placed inside aircraft wings without occupying cabin space. Therefore, optimizing the layout of hydrogen storage tanks to lower aircraft empty weight becomes the core technical bottleneck restricting the development of hydrogen-powered civil aviation.

3. Technological innovations in the design of hydrogen storage tanks

3.1. Fuselage layout scheme of liquid hydrogen storage tanks

As shown in Figure 1, three aircraft layouts compare the fuel tank arrangement of conventional kerosene planes and new hydrogen-fueled aircraft. For the traditional jet aircraft in part a, kerosene fuel tanks are neatly fixed inside aircraft wings, which makes full use of vacant wing space without taking up cabin room. In contrast, liquid hydrogen has low volumetric energy density, so hydrogen storage tanks require far more space. As displayed in planes B and C, these bulky hydrogen tanks have to be mounted within the main fuselage instead of the wings, occupying part of the inner cabin space originally for passengers or cargo.

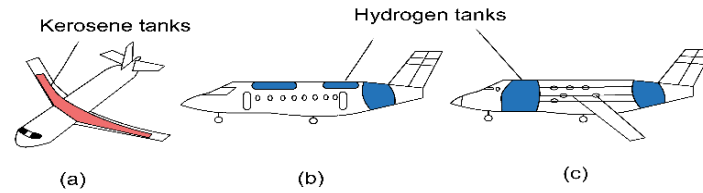


Figure 1. Fuel tank locations in (a) traditional, (b) medium-range, and (c) long-range hydrogen-powered aircraft [4]

Two fuselage tank installation modes are put forward: Full-Section (FS) and Partial-Section (PS) layouts. The FS design mounts tanks through the full fuselage cross-section and lowers passenger numbers drastically. By comparison, the PS configuration places tanks merely within cargo bays and preserves most cabin space, balancing hydrogen storage volume and passenger compartment size well [6].

When the Full-Section (FS) layout is adopted, hydrogen storage tanks mounted inside the fuselage occupy cabin space and cut the aircraft's maximum passenger load. The passenger count of modified aircraft, marked as n_p , can be calculated via Formula (1):

$$n_p = n_p^* - k_{np} \frac{n_t L_t + l_s}{l_s} \quad (1)$$

where n_p^* is the passenger capacity of the reference aircraft, k_{np} is the number of seats abreast, n_t is the number of tank groups (1 or 2, corresponding to single or multiple tank configurations), L_t is the total length of the tanks, and l_s is the seat pitch. The total tank length L_t is defined by Equation (2):

$$L_t = L_c + 2L_e \quad (2)$$

where L_c is the length of the cylindrical section and L_e is the height of each semi-ellipsoidal end cap.

Since the geometric constraints and passenger loss characteristics of the two fuselage integration schemes have been quantified, this study further investigates the structural configuration of cryogenic liquid hydrogen tanks to match aircraft cabin layout requirements. Figure 2 illustrates the structural features of liquid hydrogen storage tanks for aviation. The tank consists of a cylindrical main body and two semi-ellipsoidal end caps with outer thermal insulation layers. It is designed for cryogenic liquid hydrogen storage, featuring adjustable geometric parameters, structural support and heat preservation functions to adapt to aircraft refitting.

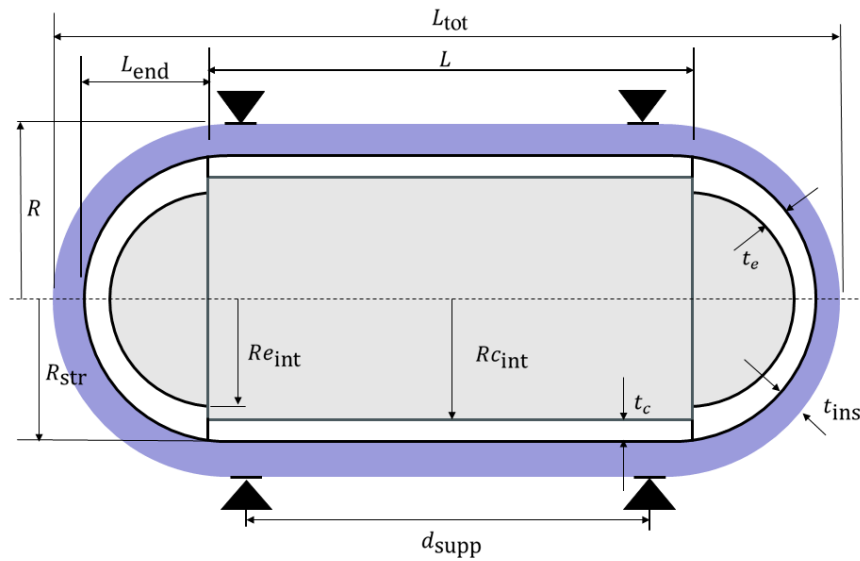


Figure 2. Lengthwise profile of a regular hydrogen tank: cylindrical mid-body paired with two semi-ellipsoidal end caps coated in purple outer insulation material [8]

3.2. Classification and performance comparison of high-pressure hydrogen storage vessels

The previous section focuses on cryogenic liquid hydrogen tanks for fuselage installation, while high-pressure gaseous hydrogen storage represents another mainstream onboard scheme with distinct structural and application characteristics. High-pressure gaseous hydrogen storage represents one of the most mature solutions for aircraft hydrogen storage. Classification of pressure vessels provides core reference for tank selection. As illustrated in Figure 3, high-pressure hydrogen tanks are categorized into five types (Type I to V) based on structural materials and winding structures. An obvious evolution trend can be observed from full-metal to all-composite structures. Type I vessels are fully metallic and widely adopted in early applications. Type II vessels use a metal liner with partial composite winding to boost pressure resistance. Type III vessels feature a metal liner fully wrapped by composite materials for higher working pressure. Type IV vessels replace metal liners with plastic ones to cut overall tank mass. Type V vessels adopt liner-free all-composite structures as the state-of-the-art design.

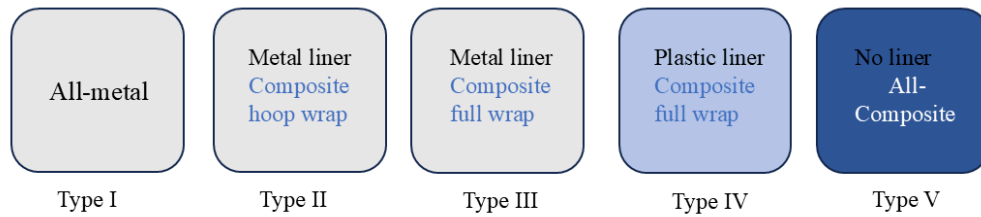


Figure 3. Graphical representation of gaseous hydrogen pressure vessels classification [9]

Table 2. Raw materials and properties for various hydrogen pressure vessels [9]

Vessel Category	Constituent Material	Mass Energy Density/(Mj/Kg)	Working Pressure/Bar	Weight Efficiency/%
Type I	All-Metal	4–5	250–700	~2
Type Ii	Metal Liner &Composite Hoop Wrap	4–5	700–875	~2
Type Iii	Metal Liner &Composite Full Wrap	4–5	875–1,100	~4
Type Iv	Plastic Liner &Composite Full Wrap	4–5	700–875	~5
Type V	No Liner &All Composite	5–8	875–1,100	~6

Table 2 records the performance parameters of five hydrogen storage tank types. All five tank designs deliver energy density between 4-8 MJ·kg⁻¹ to satisfy basic flight energy needs. Type I tanks work at the lowest pressure of 250-700 bar. Type III and Type V tanks support the maximum pressure of 875-1100 bar for better hydrogen storage density within the same volume [9]. Gravimetric efficiency acts as the core standard for aviation use. Type I and Type II tanks only reach roughly 2% efficiency. Their heavy self-weight fails to fit lightweight requirements for medium and large aircraft. Type III tanks hit around 4% efficiency and suit small and medium regional planes. Type IV and Type V tanks reach 5% and 6% efficiency respectively. They represent the most promising options for future aviation to cut aircraft empty weight and extend flight mileage.

4. Safety and economic feasibility

Hydrogen presents key economic advantages over conventional kerosene as an aviation fuel. It avoids direct carbon emissions, reducing future costs associated with carbon pricing and regulatory compliance. As renewable hydrogen production scales and technology advances, its cost is projected to become increasingly competitive with fossil-based jet fuels. Additionally, cleaner combustion minimizes engine wear, lowering long-term maintenance expenses.

Table 3. Safety and operational performance comparison of hydrogen and Jet-A fuel [10]

Parameter	Kerosene	Hydrogen
Self-Ignition Temperature	×	✓
Diffusivity	×	✓
Floatability	×	✓
Liquid Spill Risk	×	✓

Table 3. (continued)

Lower Flammability Limit	×	✓
Flame Duration	×	✓
Threshold Ignition Energy	✓	×
Gas Leak Identification	✓	×
Leak Prevention Capacity	✓	×
Flame Detection	✓	×

Note: ✓ represents the superior performance of hydrogen compared with kerosene; × stands for the performance disadvantage of hydrogen relative to aviation kerosene

However, as shown in Table 3, hydrogen also poses notable safety challenges, including a wide flammability range, low ignition energy, and difficulty in leak/flame detection, requiring specialized safety measures for its use in aviation.

5. Conclusion

Compared with conventional aviation fuels, hydrogen acts as a promising energy option for future aircraft. With continuous research and optimized design of hydrogen storage tanks, together with comprehensive evaluation on operation cost and safety risks, hydrogen energy will gradually replace fossil fuels and occupy an important position in the aviation industry. Although hydrogen has outstanding application prospects, this study still has several clear limitations. It only conducts static comparison of fuel properties and tank structures, without analyzing extra air resistance caused by onboard tanks through aerodynamic models. Its safety discussion only uses fixed data, lacking simulation of hydrogen leakage under real flight conditions. Besides, the cost analysis ignores long-term spending on tank heat preservation and regular replacement. Future research will focus on hydrogen safe delivery, proper fuselage material selection and risk elimination. Scholars should build aerodynamic matching models, develop lightweight fuselage materials with heat and leak resistance, and set up full-life cost assessment systems. In-depth research on these practical problems will improve the sustainability of hydrogen aircraft and make them widely accepted by airlines and passengers.

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