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CABIN FIRE RISKS OF HYDROGEN-POWERED AIRCRAFT: COMPARATIVE ANALYSIS AND SAFETY IMPLICATIONS

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Abstract: Liquid hydrogen (LH2) is being developed as an alternative aircraft fuel to support the decarbonisation of aviation. Although free of carbon emissions upon combustion, LH2 poses safety challenges, particularly in the confined environment of aircraft cabins. This study aims to identify potential fire hazards due to leakage and use of LH2 through a literature-based comparative analysis of kerosene. The study results show that LH2 has a wide flammability range, low ignition energy, and almost invisible flame, making early detection difficult. Cryogenic properties, explosive potential (BLEVE) and rapid gas dispersion also add to the risk. Therefore, the integration of LH2 in aircraft requires specialised detection systems, adequate cabin ventilation design and updated safety standards to suit the unique characteristics of liquid hydrogen.

Keywords: alternative fuel, cabin safety, fire hazard, hydrogen, liquid hydrogen

Introduction

Efforts to decarbonize the aviation sector have become a global priority, with the European Commission launching strategic initiatives such as the European Green Deal. This initiative aims to achieve net carbon neutrality across all sectors and EU member states by 2050, surpassing the Air Transport Action Group's (ATAG) target of carbon-neutral growth and a 50% emission reduction by the same year, with a baseline set in 2020. These ambitious goals place considerable pressure on the aviation industry to accelerate the transition toward sustainable propulsion systems (Company, 2020).

To meet these targets, the development and deployment of innovative low-carbon technologies are essential. Among the most promising options is hydrogen (H2), which can be used in aircraft propulsion either via combustion in modified engines or through fuel cells powering electric motors. Unlike conventional jet fuels, hydrogen combustion produces no carbon dioxide emissions during flight, making it an attractive solution for sustainable aviation (Baroutaji et al., 2019)

Hydrogen can be stored as compressed gas or in liquid form. Compressed hydrogen is typically suitable for short-haul flights, while liquid hydrogen (LH2), due to its higher energy density by mass, is more appropriate for medium- to long-range operations (Company, 2020; Gomez & Smith, 2019; Verstraete et al., 2010). LH2 is stored at cryogenic temperatures of approximately −253 °C (20 K), which presents both energy and weight efficiency benefits, such as reduced take-off weight, provided high-efficiency tank systems are used (Contreras et al., 1997; Rompokos et al., 2021).

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Several recent studies have explored the viability of hydrogen as an aviation fuel. For example, Holborn et al. (2022) modelled the safety aspects of liquid hydrogen in aviation applications, while Wadher (2021) proposed certification frameworks for hydrogen-powered aircraft. However, most of these studies focus on fuel system design, performance, or general safety considerations. Only a few have examined the specific implications of hydrogen-related fire hazards inside the aircraft cabin, which is a critical area given the confined nature of cabin spaces and the unique properties of hydrogen.

This study seeks to fill that research gap by focusing on fire risks to cabin safety in the context of liquid hydrogen use. It highlights how the specific characteristics of LH2 – including its wide flammability range, near-invisible flames, low ignition energy, and cryogenic storage conditions – introduce new challenges to fire prevention, detection, and containment in aircraft interiors. By conducting a comparative literature-based analysis between hydrogen and kerosene, this research contributes original insights to a largely underexplored area in hydrogen aviation safety, and proposes the need for cabin-specific mitigation strategies.

Method

This research uses a qualitative approach with a comparative document analysis method to assess the potential fire hazards associated with the use of liquid hydrogen as an aircraft fuel. The main focus of the analysis was on the safety implications within the cabin, given the confined characteristics of the cabin environment. The method was designed to compare the combustion characteristics and fire potential of liquid hydrogen (LH2) with conventional fuels such as kerosene and identify the risks that may arise in enclosed cabin space.

The methodology consists of the following stages:

1. Literature Collection
   Relevant scientific articles, regulatory documents, and technical reports relating to hydrogen were collected through academic databases (e.g. ScienceDirect, SpringerLink, and Google Scholar).
2. Selection and Categorization
   The selected documents were filtered based on relevance, publication quality, and alignment with the study's scope. The materials were then categorized into three groups:
   a) Hydrogen and kerosene fuel properties
   b) Fire and ignition behavior in confined spaces
   c) Safety incidents and risk mitigation measures in aviation
3. Comparative Analysis
   Key characteristics of liquid hydrogen and kerosene were compared using parameters such as:
   a) Flammability limits
   b) Ignition energy
   c) Flame temperature and visibility
   d) Detonation range
   e) Auto-ignition temperature
   f) Heat transfer and radiation levels
   These parameters were synthesized into comparative tables to illustrate distinctions and potential hazards.
4. Risk Mapping related to Cabin Environment
   The data was interpreted within the aircraft cabin environments. Identified risks such as microflames, jet fires, deflagrations, and BLEVE events were mapped to typical cabin

configurations to assess their practical implications on passenger safety, emergency procedures, and system design.

5. Validation Through Cross-Reference
   Multiple sources were cross-referenced to ensure consistency and reliability of the data. Special attention was given to recent publications and safety standards, including those from NASA, EASA, FAA, and ICAO.

This methodological framework enables a structured understanding of how LH2 fuel properties translate into potential cabin hazards and supports evidence-based recommendations for improving hydrogen aircraft safety protocols.

This study identified and classified the potential fire hazards associated with the use of LH2 as an aircraft fuel, especially in relation to cabin safety. The results are organized into four main categories:

1. Comparison of Hydrogen and Kerosene Properties
   A comparative analysis was conducted on the physical and chemical properties of hydrogen and kerosene fuels. Key findings are summarized in Table 1:

Table 1. Comparison of Hydrogen and Kerosene Properties
Source: (Tretsiakova-McNally & Makarov, 2016a, 2016b; Wadher, 2021)

Properties	Hydrogen	Kerosene
Flammability limits in air (vol. %)	3.9–75.0	0.6–4.7
Detonability limits in air (vol. %)	18.3–59.0	N/A
Minimum ignition energy in air (mJ**)**	0.017	0.25
Auto-ignition temperature (K**)**	~858	>500
Quenching gap at NTP (mm**)**	0.6	2.0
Boiling point at 1 atm (K)	20.27	440 to 539
Lower heating value (MJ/kg**)**	119.96	42.8
Flame temperature (K**)**	2318	2200
Thermal energy radiated to surroundings (%)	17–25	30–42
Flame visibility	Near-invisible (UV)	Visible (IR)

These data show that hydrogen has much wider flammability and detonability limits, significantly lower ignition energy, and produces nearly invisible flames. These characteristics increase the risk of undetected ignition within confined cabin spaces.

2. Specific Hazards of Liquid Hydrogen
   Through literature synthesis, unique properties of LH2 relevant to fire safety were identified:
   a) Cryogenic nature
      Contact risk (frostbite, asphyxiation), ice formation, and pressure build-up (Administration, 2017).
   b) Gas cloud behavior
      Saturated vapor density may cause downward or horizontal dispersion, increasing the risk of enclosed ignition (Molkov, 2015).
   c) Contamination hazard
      Trace oxygen contamination during storage or refueling may lead to spontaneous detonation (Administration, 2017).

   These findings underscore the need for specific containment and ventilation designs to mitigate the hazards unique to liquid hydrogen.

3. Fire Hazard Scenarios Related to Cabin Safety

Six major fire hazard scenarios relevant to LH2 leakage in aircraft cabins were extracted and tabulated below:

Table 2. Identified LH2 Fire Hazard Scenarios in Confined Spaces

Hazards	Description	References
Microflames	Undetectable flames from micro-leaks, leading to long-term degradation or fire	(Butler et al., 2009; Lecoustre et al., 2010)
Hydrogen Jet Fires	High-pressure hydrogen jets forming intense flames that may erode materials	(Clarke et al., 2023)
Hydrogen Deflagration	Flame propagation in sensitive H2-air mixtures (above 12% vol.)	(Wadher, 2021)
Hydrogen Detonation	Explosion due to flame acceleration, detonation range: 18–59% vol.	(Administration, 2017)
BLEVE	Explosion from pressurized cryogenic tank rupture	(Van Den Berg et al., 2004)
Fireball	Radiative heat ball after catastrophic tank failure	(Holborn et al., 2020, 2022; Makarov et al., 2021; Ustolin & Paltrinieri, 2020)

These hazards are all potentially relevant within cabin compartments, especially due to confined volume, limited airflow, and the presence of ignition sources from electrical systems or cabin electronics.

4. Comparison of Fire Hazards between Liquid Hydrogen and Kerosene

A focused comparison was made between the potential fire hazards of LH2 and kerosene, specifically in relation to cabin environments, where confined space, ventilation limitations, and passenger safety are critical concerns. Although kerosene has been regulated under fire safety standards, LH2 presents different hazard profiles that may pose unique safety challenges in cabin areas.

Table 4. Comparative Fire Hazard Analysis

Hazard Category	Kerosene	Liquid Hydrogen	Cabin Safety Implication
Flame Visibility	Flames are visible (infrared), allowing faster detection	Flames are nearly invisible (mostly UV radiation)	Harder to detect in cabin; delays in response and evacuation
Ignition Energy	Relatively high (0.25 mJ), requires strong ignition source	Very low (0.017 mJ), can ignite from static discharge	Increased risk of unnoticed ignition from cabin electronics or friction
Thermal Radiation	High radiant heat (30–42%), easily felt by passengers and triggers alarms	Low radiant heat (17–25%), not easily felt despite active flame	May lead to injuries before detection or visible cues appear
Flammability Range	Narrow (0.6–4.7 vol.%) in air	Very wide (3.9–75 vol.%) in air	Small leaks can result in flammable concentrations in confined space
Fire Spread in Cabin	Limited by compartmentalization and fire-resistant materials	Hydrogen diffuses quickly and may ignite at various locations	Requires containment systems and directional ventilation in cabin design
Explosion Risk	Pool fires and smoke are more common than explosions	High potential for deflagration and	Greater emphasis needed on pressure relief and blast-mitigation design

		detonation in confined cabin volumes	
Detection Suitability	Conventional optical flame and smoke detectors are effective	Optical detectors may not detect UV flame; gas sensors needed	Additional LH2-specific detection systems required in cabin infrastructure

These comparisons indicate that liquid hydrogen poses significantly different fire safety risks in confined space areas compared to kerosene. In particular, the invisibility of flames, low ignition energy, and wide flammability range make LH2 fires more difficult to detect and manage using existing kerosene-based fire protection systems regulation. Therefore, to ensure equivalent or improved safety levels, the integration of LH2 fuel systems into commercial aircraft cabins must be accompanied by:

a) Advanced fire detection systems (e.g., hydrogen gas sensors, UV/IR flame detectors),
b) Improved cabin ventilation design to control vapor accumulation,
c) Material selection and structural containment that address LH2-specific hazards.

Discussion

The use of liquid hydrogen as an alternative fuel in aviation is gaining attention due to its zero-emission potential during combustion. This makes it a prime candidate for decarbonising the global aviation sector. However, its application in commercial aircraft requires a thorough understanding of the unique fire hazards, especially in cramped cabin environments filled with complex integrated vital systems.

From the comparative analysis in this study, it is evident that LH2 exhibits significantly different fire behavior characteristics compared to conventional Jet-A fuel. These differences are not just physical but operationally impactful, especially in how fire is detected, contained, and managed within an aircraft cabin:

1. Flammability and Ignition: LH2 possesses a much wider flammability range (3.9–75 vol.%) and an extremely low ignition energy (0.017 mJ). This makes even small leaks potentially hazardous, as ignition could occur from electrostatic discharge or minor electrical faults, which are common in cabin environments. In contrast, kerosene has a narrow flammability and higher ignition threshold, providing a wider margin of safety and is already addressed by existing safety regulations.
2. Flame Detection and Visibility: The near-invisible flames produced by hydrogen combustion in the ultraviolet spectrum pose a significant challenge. Existing fire detection systems in commercial aircraft, designed for hydrocarbon fires, rely primarily on infrared and optical smoke detection. These may not function effectively for LH2 fires, delaying emergency response in cabin settings.
3. Thermal Radiation and Human Response: Unlike kerosene, hydrogen fires radiate less thermal energy and produce less visible cues. This means that passengers and crew may not immediately perceive danger, increasing the risk of unnoticed exposure before evacuation can begin.
4. Explosion Risk in Confined Spaces: The potential for deflagration and detonation in LH2-air mixtures is substantially higher than for kerosene. As shown in the results, fire scenarios such as microflames, jet fires, BLEVE, and fireballs require new cabin design approaches, including better pressure relief, leak detection, and vapor control.

From a regulatory perspective, current aircraft safety standards are largely tailored to the behaviour of kerosene and are likely to be inadequate to address the specific risks of LH2, particularly with regard to flame invisibility, rapid gas dispersion, and cryogenic storage.

Therefore, new safety standards or additional requirements will be essential before LH2-fueled aircraft can be considered safe for commercial passenger operations.

Conclusion

The transition to using liquid hydrogen as a new generation of aviation fuel is a significant step in the decarbonisation of air transport. However, this change also introduces unfamiliar safety challenges, particularly regarding fire hazards in the confined environment of aircraft cabins. Addressing these challenges requires more than just adapting existing systems, but also demands a fundamental re-evaluation of the current safety paradigm.

This study reveals that hydrogen’s properties differ substantially from conventional aviation fuels, thus requiring targeted solutions in areas such as fire detection, material durability and emergency response strategies. Existing standards, which were largely developed for kerosene, may not be suitable when applied to hydrogen scenarios. Therefore, relying solely on incremental adjustments to legacy regulations will not be sufficient to ensure passenger safety.

To move forward, aviation stakeholders must invest in dedicated research, including experimental fire modeling and real-world simulations involving LH2 in cabin environments. These efforts should inform the development of new airworthiness standards and design protocols specifically designed for hydrogen-fuelled aircraft. Only through an integrated and forward-looking approach can the full potential of hydrogen be safely and effectively realised in commercial aviation.

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