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A review on liquid hydrogen fuel systems in aircraft applications for gas turbine engines

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ABSTRACT

The transition from traditional aviation fuels to low-emission alternatives such as hydrogen is a crucial step towards a sustainable future for aviation. Conventional jet fuels substantially contribute to greenhouse gas emissions and climate change. Hydrogen fuel, especially "green" hydrogen, offers great potential for achieving full sustainability in aviation. Hybrid/electric/fuel cell technologies may be used for shorter flights, while long-range aircraft are more likely to combust hydrogen in gas turbines. Liquid hydrogen is necessary to minimize storage tank weight, but the required fuel systems are at a low technology readiness level and differ significantly from Jet A-1 systems in architecture, operation, and performance. This paper provides an in-depth review covering the development of liquid hydrogen fuel system design concepts for gas turbines since the 1950s, compares insights from key projects such as NASA studies and ENABLEH2, alongside an analysis of recent publications and patent applications, and identifies the technological advancements required for achieving zero-emission targets through hydrogen-fuelled propulsion.

Abbreviations

A	Area	He	Helium
ATI	Aerospace technology Institute	HEX	Heat exchanger
APU	Auxiliary power unit	IRAS	Integrated Refrigeration and storage
BWB	Blended wing body	LH_2	Liquid hydrogen
CcH2	Cryo-compressed hydrogen	LNG	Liquefied natural gas
CNG	Compressed natural gas	P	Pressure
ECS	Environmental control system	SAF	Sustainable aviation fuel
EECS	Electronic engine control system	T	Temperature
FC	Fuel cell	TRL	Technology readiness level
GT	Gas turbine	UHC	Unburned hydrocarbon

1. Introduction

This paper reports an in-depth analysis of liquid hydrogen (LH_2) fuel and thermal management systems for gas turbine engines in aircraft. It reviews papers and technical reports issued over the last seven decades and more recent patent publications and compares the different architectures. The goal is to shed light on the technological advancements required for achieving zero-emission targets through hydrogen-fuelled propulsion.

According to the ICAO Committee on Aviation Environmental Protection, carbon dioxide (CO_2) and nitrogen oxide (NOx) emissions are expected to increase by 21% and 16%, respectively, by 2040, relative to base year 2015 [1]. If appropriate emissions reduction measures are not taken, the aviation industry would further increase the rate of greenhouse gas emissions by 2050. This is mainly due to emissions from narrowbody aircraft powered by kerosene [2,3]. As a result, aircraft and engine manufacturers will be required to comply with strict targets for reducing greenhouse gas emissions. As part of the Flight Path 2050 initiative, the Advisory Council for Aeronautics Research in Europe has set ambitious goals for future civil aircraft. These include a 75% reduction in CO_2 emissions per passenger kilometer and a 90% reduction in NOx emissions, compared to typical aircraft in the year 2000 [4].

The aviation industry now shows great interest in moving from

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[1] With the deepest regret, Dr Jon Huete Anton passed away in August 2024. In recognition of his invaluable contributions and in honor of his memory, the remaining authors have chosen to complete and submit this work with his name included as a co-author. This serves as a tribute to our esteemed friend, colleague, and mentor.

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conventional fuel to sustainable and low-emission fuels and electric power. Sustainable Aviation Fuel (SAF) is a drop-in replacement for kerosene, but liquid hydrogen (LH_2) is seen as the longer-term more economical solution, as illustrated in Fig. 1.

Interest in hydrogen is evident in several international projects, such as Airbus's ZEROe initiative [6], which aims to introduce hydrogen-powered commercial aircraft by 2035. The H2Fly project [7] is pushing the boundaries of hydrogen fuel cell technology in aviation. ZeroAvia [8] is at the forefront with hydrogen fuel cell technology. Universal Hydrogen [9] proposed an innovative modular hydrogen distribution system and a retrofit kit for regional airplanes. Cranfield Aerospace Solutions (CAeS) [10], and the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) [11], are also contributing to the goal of net-zero emissions, with the Hydrogen Islander Demonstrator Aircraft, and research on cryogenic hydrogen fuel cell systems.

Hydrogen is an excellent carbon-free energy storage medium. It was extensively studied during the 1950s in the search for improved performance, and in the 1970s following the first fuel crisis. Now, with the increasing environmental concerns, it is being re-examined as a long-term energy solution, particularly for short-range aircraft [12]. These aircraft have the potential to greatly reduce the environmental impact of civil aviation. Drop-in-replacement biofuels and synthetic jet fuels, needed for legacy aircraft, will not offer significant mission-level reductions in CO_2, CO and Unburned Hydrocarbon (UHC) emissions. This is because they retain similar physical and chemical properties to Jet A-1. They may still generate particulates from incomplete combustion of the cyclic aromatic hydrocarbons added to plasticize elastomeric seals to avoid fuel system leaks (though there might be some benefit to UHCs and particulates from drop-in SAF if naphthalenes are minimized). Hydrogen will not generate any of these mission-level emissions, though some emissions may still result from engine oil consumption [5,13].

There is an ongoing controversial discussion as to whether liquid hydrogen is the solution for long-range aircraft or whether SAF must be used in these aircraft. For example, a study at the University of Cambridge [14] evaluated the performance of large liquid hydrogen (LH_2) passenger aircraft against liquified natural gas (LNG) and other alternative fuels, including dual-fuel solutions. It found that, while LH_2 offered performance advantages, it led to increased energy consumption for hydrogen liquefaction and required a larger number of aircraft due to storage constraints, resulting in carrying fewer passengers. Conversely, studies such as ENABLEH2 [15], FlyZero [16–18] have predicted that long-range LH_2 aircraft will become feasible well before 2050. It should be noted that compared to other storage methods, such as cryo-compressed storage, liquid hydrogen storage offers advantages in terms of higher energy density per unit mass, reduced weight due to lower pressure requirements, and established technology [19,20].

The initial focus for aircraft powered by LH_2 will be on demonstrating safety and achieving certification, both for gas turbine and fuel cell systems. These first two innovation waves may be followed by more efficient and longer-range aircraft designs and by the synergistic integration of advanced propulsion systems with unconventional airframe configurations. This gives four possible innovation waves, as illustrated in Fig. 2.

Overall life cycle or 'well to wake' emissions are dependent on the fuel sourcing, processing, distribution, and storage. There are several potential routes for hydrogen production, including renewable energy, nuclear power, and fossil fuels [21]. The main route for hydrogen production is currently from fossil fuels. Carbon sequestration should limit the life-cycle CO_2 emissions, but to ensure an environmentally sustainable 'hydrogen economy,' it will be necessary to rely on renewable or nuclear energy for 'green' or 'pink' hydrogen production and for hydrogen liquefaction.

Hydrogen diffuses very rapidly, and it has wide flammability limits, which makes it ideal for use in lean combustion systems that limit the high flame temperatures that increase NOx production. Relative to other fuels, hydrogen's high flame speed also enables combustor designs with lower residence times at peak temperatures, further helping to reduce NOx generation. Micromix technology offers ultra-low NOx combustion, without the inherent risk of auto-ignition and flashback often associated with lean-premixed combustion systems [22].

Hydrogen does have some drawbacks. For example, hydrogen may escape more easily from inside fuel systems than other fuels, requiring more sophisticated designs to guarantee safe operation [23]. Also, while its specific energy is almost three times that of conventional jet fuels like Jet A-1 (120 MJ/kg, relative to 43 MJ/kg), the volumetric energy density of LH_2 is lower (typically 8.48 MJ/m^3, relative to 33.7 MJ/m^3). Therefore, the tanks needed to store the same amount of energy will have about four times the volume [12].

LH_2 is stored at low pressure (a few bar) and at low cryogenic temperatures (around 21–27 K) to maximize its density. Its tanks and fuel systems require advanced insulation systems to limit leakages and heat ingress, and need ventilation strategies with correct installation to minimize risks associated with the formation of flammable vapor concentrations [24,25].

The fuel system will be a two-phase dynamic fluid circuit in which hydrogen is mostly liquid in the tanks, but is delivered to the power generation element (a gas turbine combustion chamber, piston engine or fuel cell) in gaseous form. Therefore, phase change will take place in the system. This means that, at various times, some components may work with the liquid phase, the supercritical or gaseous phase, or a two-phase regime. Where phase changes occur will depend on the system architecture, boundary conditions and operating conditions [26].

Heat transfer depends on the thermal management system design, insulation systems and materials, boundary conditions and fluid states. Most studies are based on numerical models and existing control algorithms, as relatively few component-level experimental studies are available in the public domain [22,27,28].

2. Review of the literature on gas turbine engine liquid hydrogen fuel systems

It is beneficial to see the overall trend of public domain research publications relating to hydrogen-powered aviation from 1950 to 2023. Using the Scopus database [29] with 'Liquid hydrogen propulsion' keywords, around 1000 documents were found. Their distribution by year is indicated in Fig. 3.

An increase in the level of interest in investigating LH_2 propulsion systems is evident. In more detail the publications may be divided into three time periods: Phase 1: 1950–1996, Phase 2: 1997–2006, and Phase 3: 2007–2023. In Phase 1, the idea of liquid hydrogen for aircraft propulsion emerged, notably in NASA studies. As the network grew in Phase 2, there was an increase in interest in research regarding aircraft components. Phase 3 involved hydrogen and liquified gasses as significant

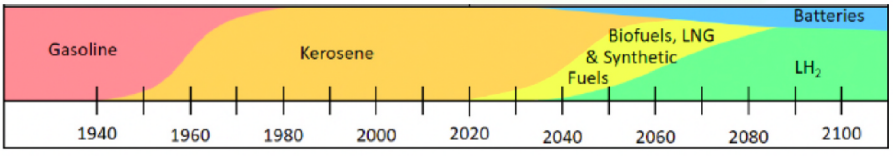


Fig. 1. A pathway for decarbonizing aviation [5].



Fig. 2. Liquid hydrogen-fuelled aircraft innovation waves for gas turbine (GT) and fuel cell (FC) power (Images sources [6,16]).

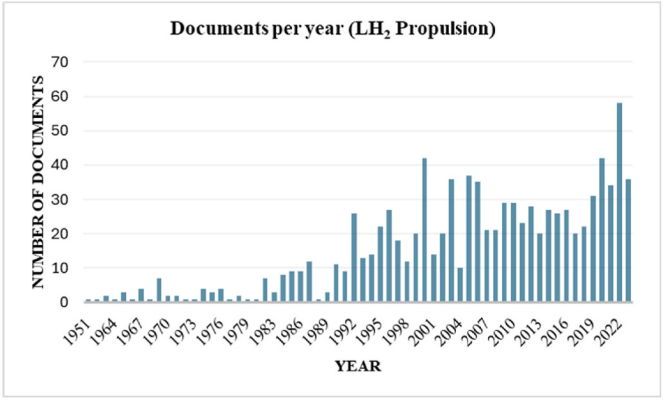


Fig. 3. Liquid hydrogen propulsion-related papers by year.

components of the overall network, including fuel cells. These trends provide the basis for current research topics in hydrogen-powered aviation as a significant element of so-called 'green aviation' studies. The images in Fig. 4 were produced by VOSviewer [30].

Another consideration for the keywords was added because the primary purpose of this paper is reviewing LH_2 fuel systems needed for gas turbine engines. Consequently, many articles discussing hydrogen-fuelled aircraft or fuel cells were not relevant. A recent study from the University of Surrey [31] presents a detailed review of liquid hydrogen propulsion technologies in aircraft. That study primarily focused on the top-level configuration analysis of the aircraft propulsion systems and fuel cells with hydrogen. Another study [32] provided an overview of thermal management system architectures for hydrogen propulsion systems and identified the research gaps. However, neither of these sources provides in-depth information about the hydrogen fuel systems used in aircraft gas turbines or their advancements over the past 70 years. The current study focuses on this specific area. However, the engine fuel systems cannot be considered without some reference to fuel systems on the rest of the aircraft. After selecting particular keywords, only a minority of the initially identified publications were found to be relevant.

System and technology studies proposed in projects at NASA, Lockheed, Tupolev, Airbus, etc., are reviewed in the following sections, outlining their advantages and disadvantages, and some research gaps.

3. Liquid hydrogen fuel systems for aircraft

3.1. Design and performance evaluation of a turbojet fuel control system in an experimental aircraft

The 1957 NACA research memorandum from Otto et al. [28] presents design and performance evaluation of the fuel control system in an experimental B-57 aircraft with a hydrogen burning J65 turbojet engine. In order to reduce the required hydrogen volume, the flight plan was divided into separate parts. For take-off and climb, the aircraft used conventional JP-4, and for high-altitude operation, one engine used hydrogen, stored as a liquid in a dedicated tank. The overall hydrogen fuel system architecture is shown in Fig. 5. A fuel control system that

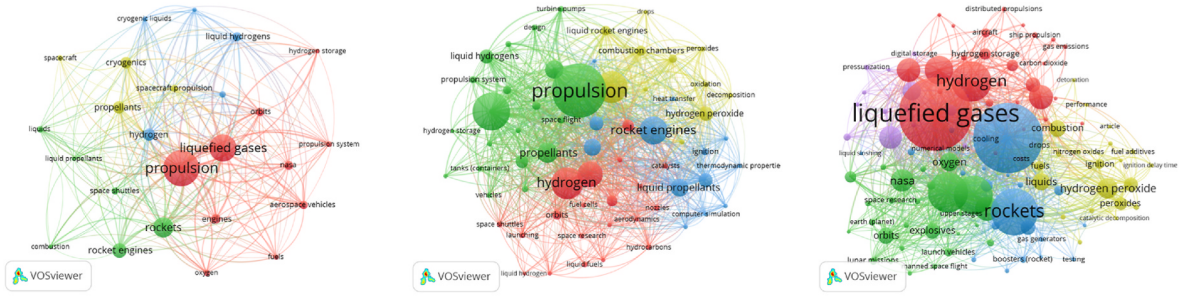


Fig. 4. Network structures of keywords developed over three time periods (a: phase 1, b: phase 2, c: phase 3).

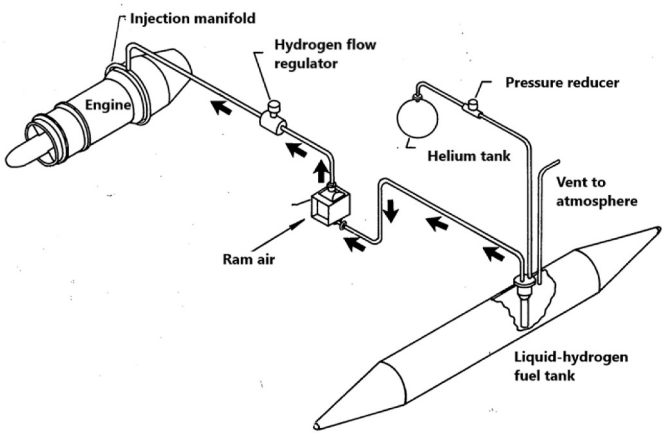


Fig. 5. B-57 hydrogen fuel system [28].

was compatible with the two fuels (JP-4 and hydrogen) was used. The JP-4 fuel system was left intact, and a differential reducing valve, which controlled the flow by maintaining a pressure drop, was added as a flow regulator to the system as shown in Fig. 6.

The B-57 fuel system used helium for pressurization. However, this is generally considered an unacceptable solution for aviation, because helium is expensive and in limited supply. Its routine use for pressurizing fuel systems would seem unsustainable where there would be widespread adoption of hydrogen-fuelled aviation.

The hydrogen fuel system was designed just for the delivery of low pressure and low temperature gas at high altitudes. This reduced its complexity. For comparison, a modern turbofan engine fuel system would need more powerful pumps and heat exchangers to raise the pressure and temperature of the fuel.

The aircraft had dual-fuel systems (JP-4 and hydrogen), a configuration that does not offer mission-level decarbonization for civil aviation as it produces carbon emissions. It also increases the number and complexity of fuel systems on the aircraft. Controlling hydrogen fuel flow using a second fluid seems impractical today for purely hydrogen-fuelled engines. However, engines that currently use kerosene in their actuation systems for variable vanes, would need to find alternative design solutions for vane actuation when converted to hydrogen fuel.

Venting of hydrogen overboard, to prevent over-pressure conditions, reduces energy efficiency. An aircraft with poorly insulated tanks, that needed to vent hydrogen during cruise, would also be unable to store the LH_2 on the ground for very long without venting some boil-off gas. The time an aircraft can spend without needing to vent some gas is referred to as the dormancy time. Venting hydrogen at airport gates raises safety issues.

3.2. Flight investigation of a liquid hydrogen fuel system

A NACA memorandum from Mulholland et al. [33], describes the practical implementation and flight testing of the B-57 fuel system utilizing hydrogen in one of its two J65 turbojet engines, as outlined in Ref. [28]. The fuel system was designed to supply hydrogen at the required rate for about 30 min flight at 50,000 ft altitude and 0.72 Mach number. Fuel system components included a hydrogen fuel tank mounted at one wing tip, helium tanks, a heat exchanger and a control valve, as shown in Fig. 7a The hydrogen fuel control regulator was a constant ratio valve, and the hydrogen fuel supply included two shutoff valves: valve 5 (fuel supply) near the liquid line and valve 3 (manifold shutoff) near the vapor line. The fuel tank vent valve (valve 10) was manually operated to release the build-up in tank pressure.

Three test flights were made with this fuel system. For the in-flight transition from JP-4 to hydrogen, first the LH_2 tank was pressurised by helium, then the fuel line was purged with nitrogen before the switch was made to the dual-fuel mode.

Helium was used for pressurization because originally no suitable liquid hydrogen pump was available for aircraft. The hydrogen tank was designed to operate at 3.44 bar gauge pressure, which was adequate because the engine had very low overall pressure ratio and was only operated on hydrogen at high altitude.

Eight venting operations were required during the mission (climb to cruise). Since the venting process was conducted manually by the flight engineer, the tank pressure differed on each occasion. A large pressure drop was observed between a first and second venting (52% drop). This was attributed to air turbulence causing sloshing in the fuel tank. This demonstrated the importance of considering fuel sloshing phenomena.

For further test flights, the fuel system was modified by adding a five-

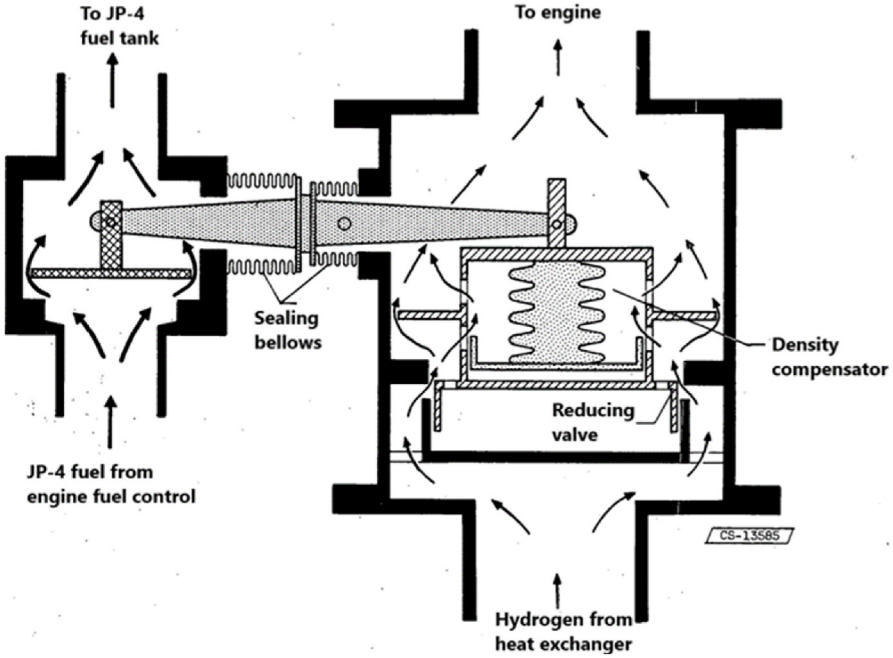


Fig. 6. B-57 JP-4 and hydrogen fuel ratio regulator [28].

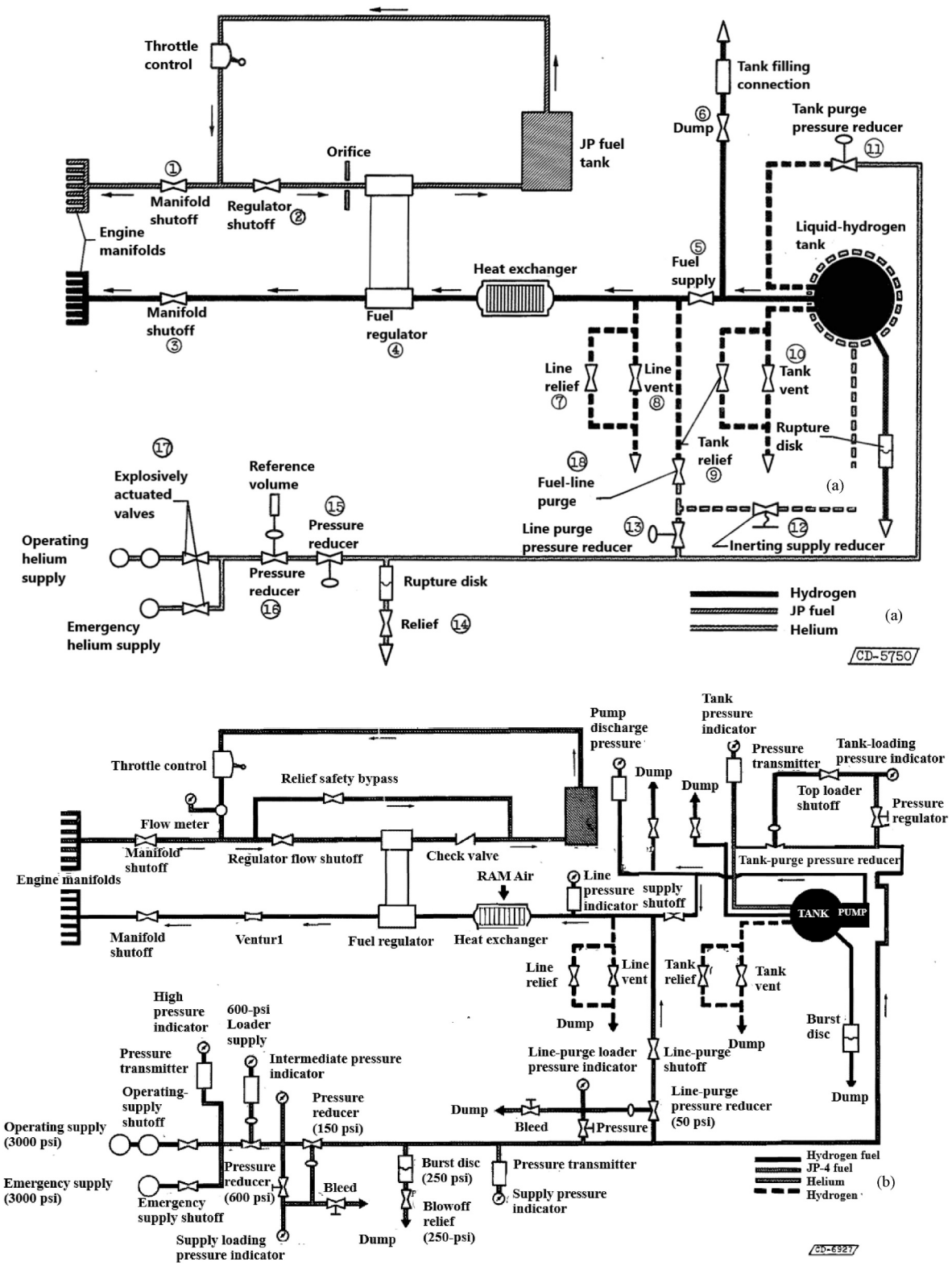


Fig. 7. B-57 liquid hydrogen fuel system schematic diagram (a: original with helium [33], b: modified with pump [34]).

cylinder reciprocating pump, as shown in Fig. 7b [34]. Helium was still used for purging, but was not used to pressurize the system. The pump was submerged at the bottom of the hydrogen tank and intended to provide a constant absolute discharge pressure of around 3.65 bar. Three flights were successfully completed, but some pressure fluctuations were observed, initiated by the initial rapid filling of the heat exchanger with LH_2. This was followed by a pressure increase that stopped the pump flow until the pressure dropped below the set value as the engine consumed the excess fuel. Oscillations in pump speed and discharge pressure continued, but despite the oscillations, the flow regulator was able to maintain a constant engine speed.

References [33,34] detailed the actual flight experiences, including the handling of pressure build-up in the fuel tank, the performance of the heat exchanger and pump, and the practical aspects of switching

between JP-4 and hydrogen fuel in flight. In contrast, the previous report [28] had identified potential stability issues with the hydrogen fuel system and the design of a control system to mitigate these issues.

Reference [33] noted that venting had resulted in 16% fuel loss. Reference [34] advocated using the positive displacement pump to pressurize the hydrogen instead of relying on helium. It argued that enabling thinner tank walls, and removing some of the high-pressure helium tanks, would balance-out the extra weight of a pump.

Relying on manual control of venting boil-off gas to the atmosphere would be considered unacceptable today.

3.3. A hydrogen and methane fuel system for a turbojet engine

A 1973 report by Goldsmith and Bennett [35] relates to the ground testing of a hydrogen and methane fuel system for a J85 turbojet engine. It expands the concept of utilizing various fuels and comprehensively covers system design, dynamic modelling, and the extensive testing conducted on the engine. The hydrogen and methane fuel systems were totally independent. The report provides detailed data for LH_2 fuel systems with a block diagram for modelling.

The LH_2 was supplied at temperatures in the range of 20–23 K and at about 2 bar absolute pressure. A main fixed-displacement, reciprocating pump discharged the hydrogen at 20–35 bar with an exit mass flow of around 0.14 kg/s. The fuel regulating valve reference point was set to about 17 bar and the burner inlet pressure was about 7 bar. The hydrogen fuel system schematic is shown in Fig. 8.

The testing was conducted in a controlled ground-based environment. The engine was run successfully on LNG, which was used as a substitute for pure liquid methane due to its availability. The tests demonstrated stable system performance and engine control from starting to maximum engine speed.

Testing with LH_2 was partially successful. The system and engine control were stable up to 88% engine speed, but the fuel pump's performance limited the maximum fuel flow and engine power available. Testing was terminated after the LH_2 fuel pump experienced a failure in its hydraulic drive motor.

The air-fuel heat exchangers for both LH_2 and LNG were able to gasify the fuel without airside freezing, but development was needed for the cryogenic fuel-oil heat exchangers to prevent freezing. Significant errors were found between the test results and those calculated, because the viscosity of the oil was not correctly modelled at different temperatures. It was recommended to use more precise oil properties in future simulations.

The tests demonstrated that an acceptable and responsive control system configuration can be achieved for a turbojet engine that uses liquid hydrogen or liquid methane. This was achieved by using liquid fuel pumping, gasification of the pump discharge flow and gas-phase flow metering.

Previous references [28,33,34] had addressed early-stage challenges, such as handling dual-fuel systems, managing fuel tank pressure, and achieving stable combustion with hydrogen. However, this project advanced the state of the art by integrating sophisticated control systems, employing supercritical pressure gasification, and addressing the thermal challenges of using liquid hydrogen and methane fuels.

3.4. Lessons from early NACA and NASA studies

A review of NACA and NASA research investigations from 1950 onwards, relevant to gas turbine engine LH_2 fuel systems, was produced by Esgar in 1974 [36]. It was reported that stable and responsive fuel control systems can be engineered, and that hydrogen can be used for oil cooling, turbine air cooling and cooling for cabin air conditioning. It also noted that heat exchanger technologies existed that could prevent oil congealing and frost formation. However, the report did identify the need for more research in the following areas:

- The long-term effects of hydrogen embrittlement
- LH_2 pump development for reliability and long-life
- Fuel handling, storage, and thermal insulation systems
- The impact of large tanks on aircraft structures and aerodynamics

3.5. NASA–Lockheed 1970s hydrogen-fuelled subsonic transport aircraft studies

Lockheed, together with NASA, published two reports describing hydrogen-powered turbofan engine studies for a long-range subsonic aircraft [37,38]. Based on this work, Brewer published the book 'Hydrogen Aircraft Technology' [39] in 1991, covering the detail design

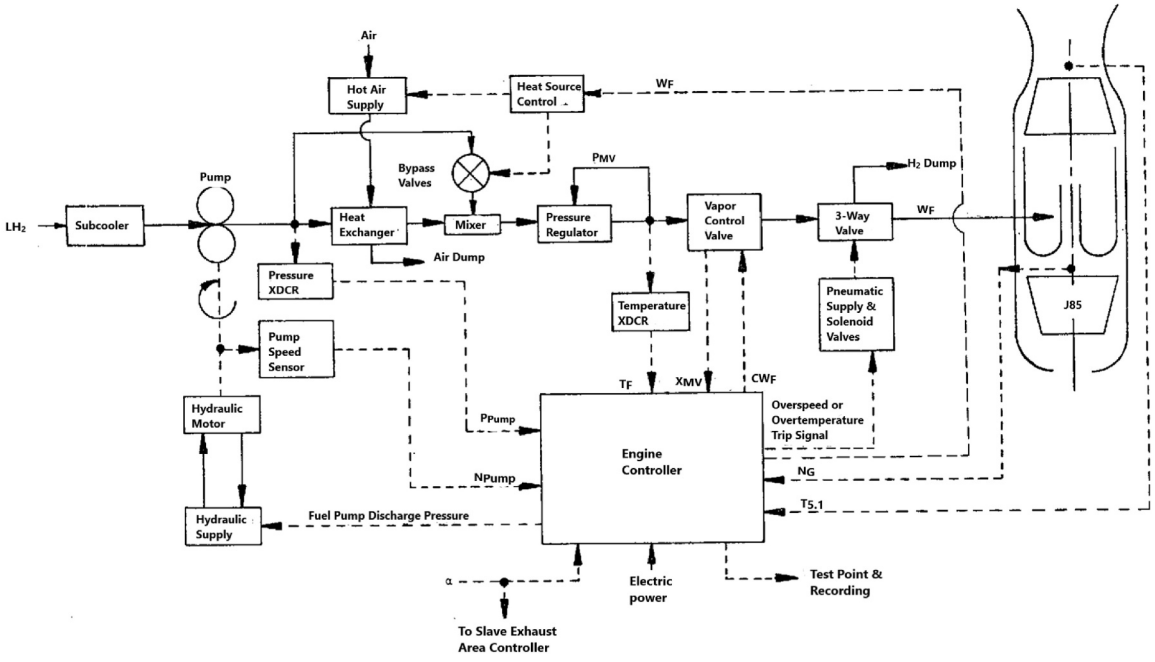


Fig. 8. J85 liquid hydrogen fuel system [35].

of hydrogen fuel systems for aircraft applications.

The fuel system architecture shown in Fig. 9 was developed for a CFM56-5B size high bypass ratio turbofan engine. Aero-thermodynamic data was provided for preliminary analyses, together with a methodology for LH_2 fuel system component selection. The same logic was also applied to LNG fuel systems [40].

The LH_2 tanks were designed to operate at a nominal 1.45 bar absolute pressure and 21.3 K temperature. Tank design pressures were lower than in previous studies in order to minimize tank weights. To compensate for this, electrically-driven booster pumps, submerged in the tanks, raised the LH_2 delivery pressure to around 3.1 bar. The tanks would be maintained at the target pressure by a pressure regulating mechanism. Venting was used in case the pressure rose to 1.52 bar, and warm gaseous hydrogen (GH_2) was injected if the pressure fell to 1.24 bar. Rather than using the engines to provide warm hydrogen, each tank was to have a dedicated heat exchanger (using Calrod heating elements). Unlike in most previous studies, helium was not used to pressurize the tanks. The high pressure pumps on the engines were mechanically driven from the engine gearbox to give about 47 bar at take-off conditions.

Heat exchangers on the engines used the hydrogen for cooling the turbine cooling air and the engine oil, and also in the environmental control system (ECS). They worked in series, together with a final turbine-exhaust heat exchanger, to increase the temperature of the hydrogen prior to burner injection. For example, this would raise the hydrogen temperature at cruise conditions from 50 K to 677 K.

Alternative arrangements of heat exchangers for heating-up the LH_2 were investigated. Four possible options are shown in Fig. 10. The Compressor precooler was quickly discounted as the benefits did not compensate for the problems the technology presented, i.e., severe air-side freezing, considerable pressure drops, too many hardware changes, and a significant weight increase.

Although the compressor intercooler presented performance benefits, the drawbacks were still considered significant. However, later studies [41–43] have contended that those drawbacks can be minimized when a new compression system is designed together with an intercooler. The turbine cooling air heat exchanger uses hydrogen to cool the cooling air used for cooling the high-pressure turbine's blades. This showed more promising results, as it was easier to incorporate into existing engine architectures. Cooling the cooling air makes it more efficient as less mass flow is required [44]. The exhaust gas heat exchanger was considered to be the most promising concept. The high temperature differential allowed for a reasonably small heat exchanger that could be integrated relatively easily into existing engine architectures.

Reference [39] provides sufficient data on the engine thermodynamic cycle and the fuel system components for their preliminary sizing and analysis, such that the number, type and arrangement of fuel system components can be reconsidered. For example, in 'more electric' aircraft, like the Boeing 787, there is no need for an ECS heat exchanger on the engine, since the air-conditioning system is operated entirely electrically [45]. However, in these reports, hydrogen is considered as pure liquid, which is unrealistic due to its potential two-phase flow behaviour below its critical pressure.

3.6. The MTU, Pratt & Whitney, and KSPA TRUD project

This study, reported in 1994, compared hydrogen vaporizer systems using either compressor air or turbine exhaust gas for heat input. These alternatives are shown in Fig. 11. However, the turbine exhaust gas is more likely to freeze on heat exchanger tubes because of its high water vapor content [41]. In a more advanced system, the hydrogen is highly compressed, and therefore somewhat warmed, before passing in series through an intercooler and an exhaust gas heat exchanger. The hydrogen is then partially expanded through a turbine, which may generate power to drive the LH_2 pump, before it provides oil cooling on its way to the combustor [46]. However, the report lacks a detailed analysis of the fuel system configurations.

3.7. An experimental turbofan using liquid hydrogen and liquid natural gas as a fuel

In 1990, Sosounov and Orlov published a report on the outcomes of the TU-155 flight campaign that demonstrated successful engine operation with LH_2 and LNG [47]. To date, this is the only experimental aircraft to have flown with a large hydrogen-fuelled gas turbine aero

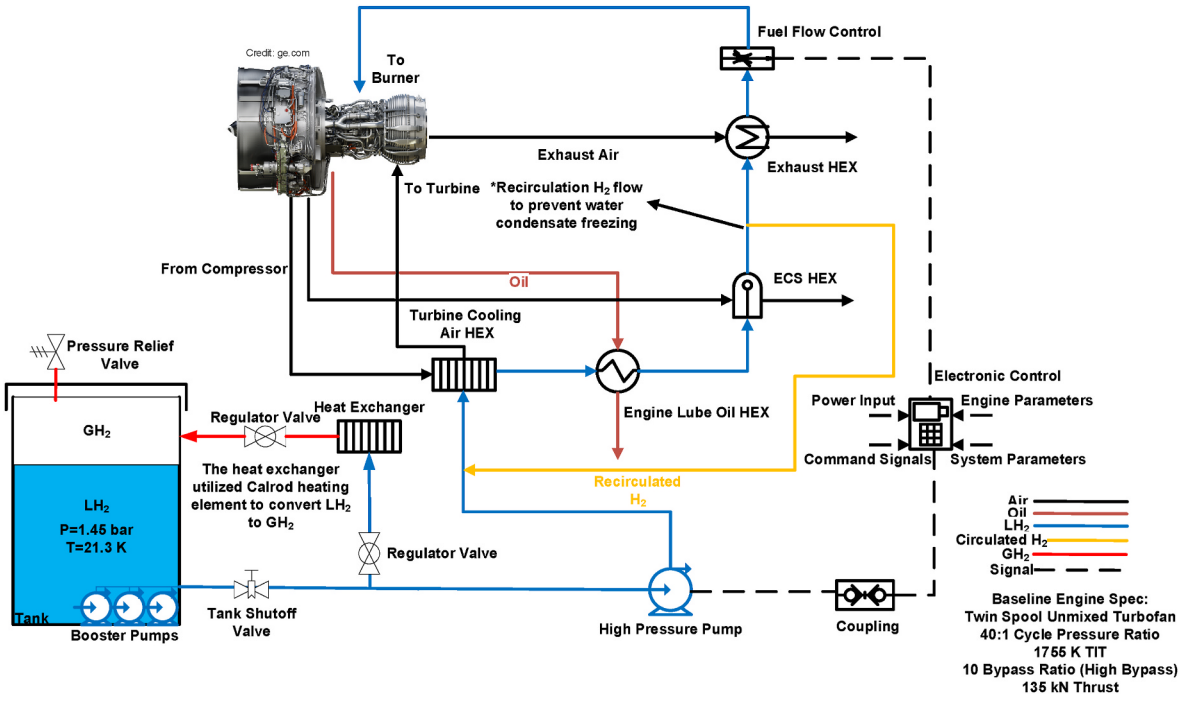


Fig. 9. NASA–Lockheed liquid hydrogen fuel system.

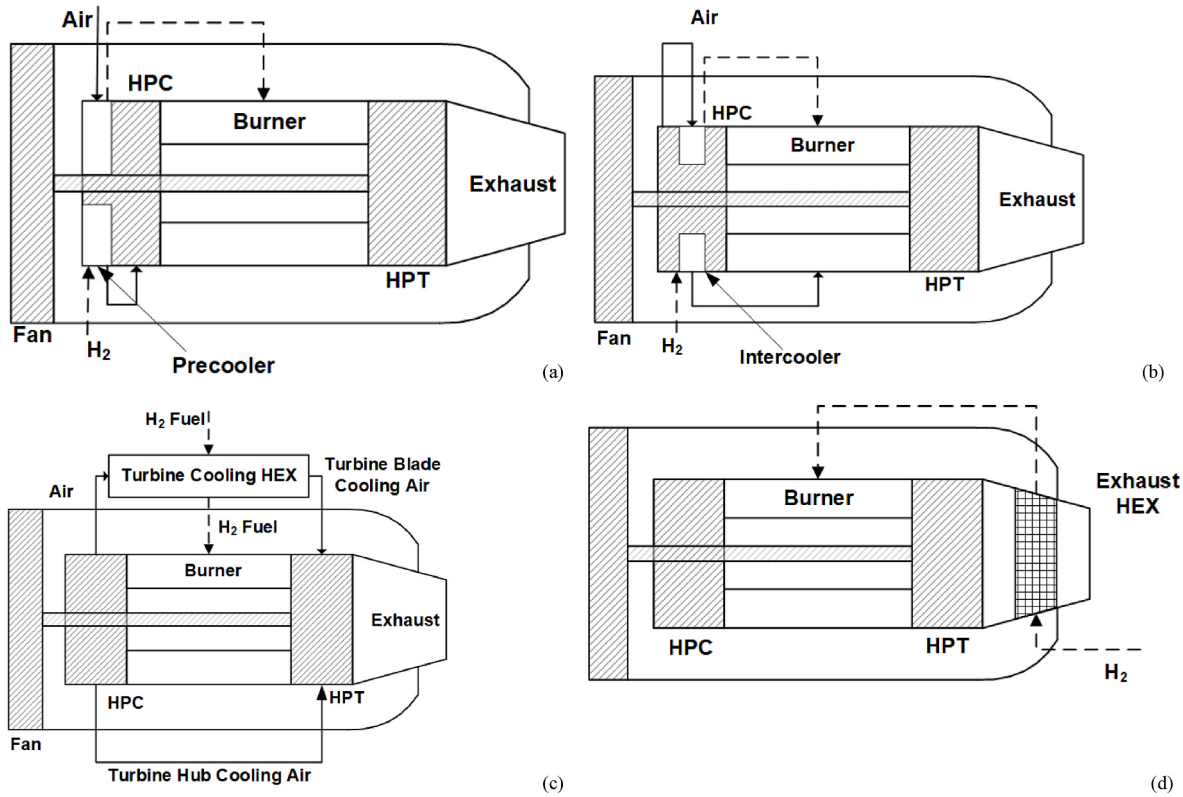


Fig. 10. Heat exchanger arrangements (a: precooler, b: intercooler, c: turbine cooling air, d; exhaust gas) - adapted from [39].

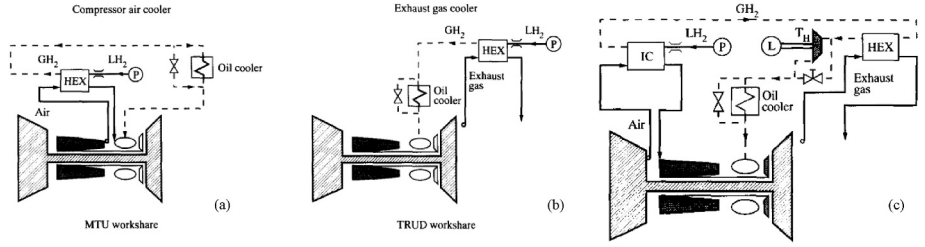


Fig. 11. Different fuel heater arrangements (a: compressor air cooler, b: exhaust gas cooler, c: integrated configuration) [46].

engine. Fig. 12 shows its arrangement with one of the three low-bypass two-spool Kuznetsov NK-88 turbofans modified to run on cryogenic fuels. Two different control schemes were developed. The initial open-loop scheme retained the kerosene fuel feed and control systems, and the hydrogen fuel pump was driven by a separate energy source. In the later, more efficient, closed loop scheme, the hydrogen was heated in a turbine exhaust heat exchanger and expanded through a hydrogen turbine to provide the power required for the hydrogen turbopump. The two systems are shown schematically in Fig. 13. There was no clear explanation for retaining the kerosene fuel system alongside the hydrogen fuel system.

The two-stage centrifugal pump delivered a pressure rise of 37 bar, with a fuel mass flow of 0.64 kg/s. At its rotational speed of 50000 rpm, the turbopump absorbed 63 kW.

During initial tests, significant instabilities were seen when hydrogen entered the combustor at temperatures below 60 K. An investigation showed that preheating was necessary and that the best position for the heat exchanger was at exit from the turbine.

3.8. CRYOPLANE

The CRYOPLANE project investigated LH_2-fuelled civil aircraft and their propulsion systems. It was led by Airbus Deutschland GmbH and the main study was for an aircraft based on the Airbus A310. Little information is available in the public domain, other than the final report summary, published in 2003 [49]. A key conclusion was that an aircraft using liquid hydrogen would not be less safe than ones using Jet A-1.

In relation to the CRYOPLANE project, a study by Corchero and Montañés presented findings on the efficiency of engines powered by hydrogen [50] CRYOPLANE assessed two options for fuel storage, at either above or below the critical pressure of 13 bar.

Since the supercritical option would need a heavier tank and more complex ground operation, the two-phase storage option was selected. The tank pressure would be kept above 1 bar.

Several different tank configurations were studied. It was concluded that the aircraft wings did not provide suitable areas for LH_2 storage, but tanks could be mounted within the fuselage. Three internal low-pressure pumps should be provided inside each tank. Two pumps would work in normal operation, with the third one kept in standby mode for redundancy.

For the engine fuel system, centrifugal high-pressure pumps were specified. For low-viscosity fluids like hydrogen, centrifugal pumps generally offer better performance than positive displacement pumps [51]. Relative to the control system for Jet A-1, the hydrogen control

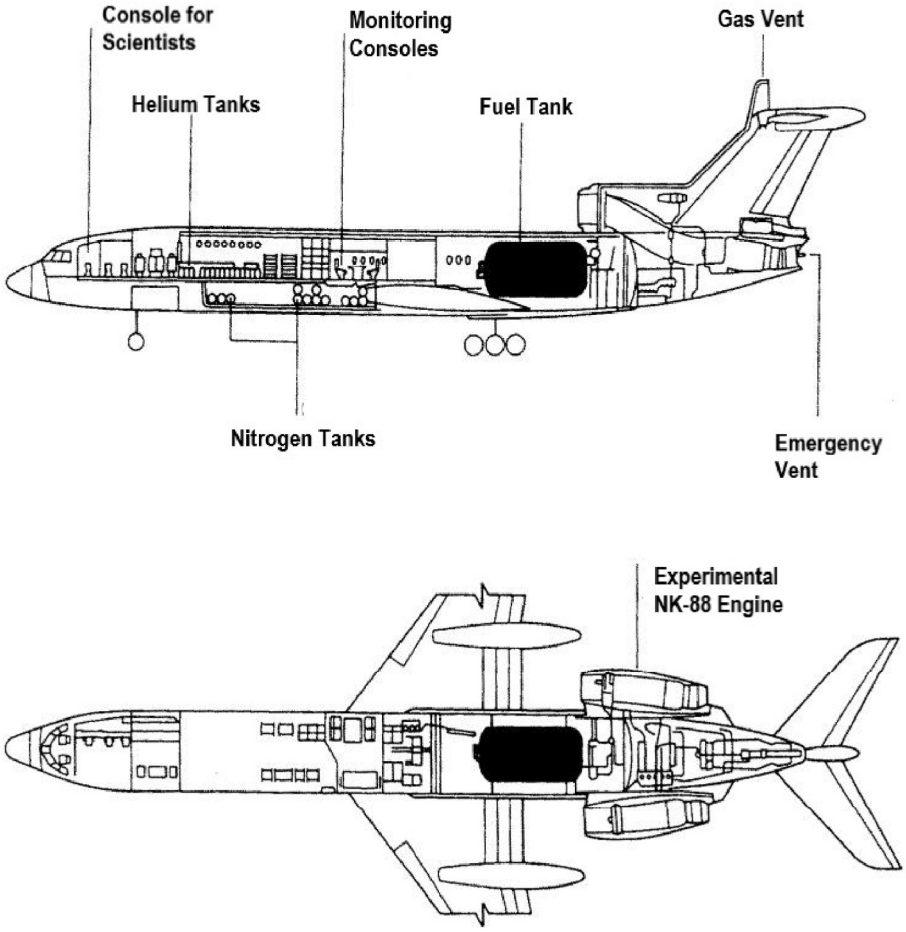


Fig. 12. Tu-155 aircraft configuration [48].

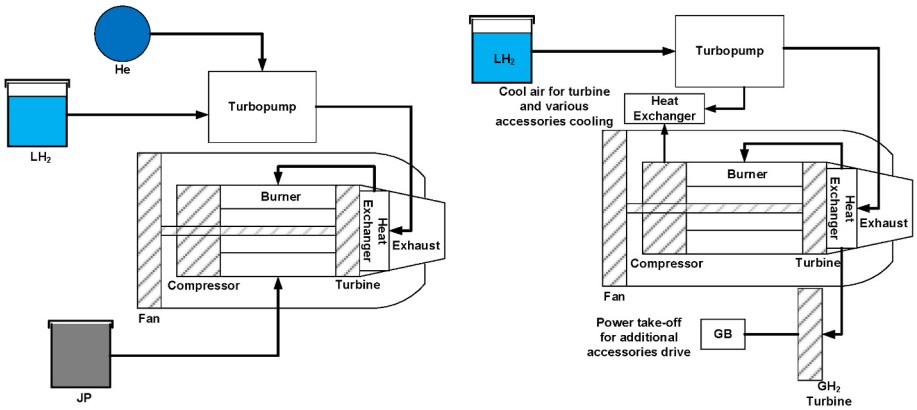


Fig. 13. Open-loop (left) and closed loop (right) systems, adapted from [47].

system needed more components and had more complicated functionality, considering the additional requirements for safety, temperature and pressure control, and leak management.

The hydrogen fuel control system had two main parts, the first when hydrogen was in the liquid phase, and the second when it was in the gaseous state after a heat exchanger. The second part was mainly based on a hydrogen fuel metering system for GTCP36-300 APU. This APU is a single-shaft engine used in A320 that was modified to run on gaseous hydrogen instead of Jet A-1. The hydrogen temperature and pressure were measured at multiple locations to enable the controller to compensate for its compressibility in the gaseous state.

3.9. ENABLEH2

This EU Horizon 2020 project 'ENABLing cryogEnic Hydrogen based CO_2 free air transport' [15] was funded by the European Commission and coordinated by Cranfield University. The primary objective of ENABLEH2 was to address the ambitious 'Flightpath 2050' targets for a 75% reduction in CO_2 and 90% reduction in NOx emissions in the aviation sector relative to the year 2000.

Key components of the project included experimental and analytical work on two main technologies: hydrogen micro-mix combustion and fuel system heat management. These technologies were evaluated for

different classes of aircraft, including advanced tube and wing and blended wing body (BWB) aircraft that featured distributed turbo-electric propulsion systems and boundary layer ingestion.

For the liquid hydrogen fuel system heat management, a couple of architectures for a turbofan engine were proposed. The main objectives of the heat management system were warming up the hydrogen from cryogenic temperatures to around 450 K before injecting it into the combustion chamber. In the heat management and fuel distribution systems proposed by Chalmers University, the LH_2 coming from the fuel tank is compressed via booster pumps, inline pumps and high-pressure pumps. The hydrogen passes through several valves and heat exchangers that may provide oil cooling and cooling for turbine cooling air. The hydrogen distribution system shown in Fig. 14 shows further options for fuel system heat management, including a hydrogen turbine for energy recovery, and Fig. 15 shows a possible fuel distribution system [40].

In the heat management systems, the focus was on the arrangement of heat exchangers in different locations on the engine in order to manage the heat transfer between the heat sources and sinks effectively. The candidate architectures potentially included a fuel-cooled precooler ahead of the core, a fuel-cooled intercooler between core compressors, and a recuperator using turbine exhaust gas to preheat the fuel. Based on analysis from Ref. [42], it appears that the precooler would not significantly improve the engine's cycle performance. Located just behind the fan, the air flow through the precooler has high Mach number that will create high pressure losses. Designing for higher effectiveness, by increasing the heat transfer area, could even have a negative impact on overall engine performance due to increasing pressure losses that would not be sufficiently offset by the benefit of the increased fuel temperature. There is also the risk of guide vane icing producing additional pressure loss if the incoming air is humid. It was concluded that further studies of precooling were not merited. This outcome is consistent with previous studies from Ref. [39]. The intercooler was also predicted not to significantly benefit engine performance, across a broad range of heat exchanger effectiveness levels, unless the compression system would be redesigned to increase the engine overall pressure ratio.

It was concluded that there was potential to preheat hydrogen more economically using the combination of intercooler and recuperator, instead of the precooler and intercooler.

In [41], conceptual design studies analyzed the impact of intercooling and recuperation on engine architecture and mass. Linear trade factors were used to evaluate the resulting concepts for short-medium range aircraft, based on fuel burn performance. The highest reduction in fuel burn was observed for the recuperated concept, which amounted to 5.1%, while the intercooled and recuperated concept, which was heavier, still resulted in a fuel burn reduction of about 4.8%. Ultimately, the intercooled and recuperated concept was selected due to its substantial fuel burn reduction, reduced core temperatures, and the prevention of icing in the recuperator by preheating the hydrogen in the intercooler. However, proper intercooler design was vital to prevent air freezing and icing in the intercooler. In Ref. [43], the concept of recirculating LH_2 in the intercooler was introduced to raise its temperature above 100 K. Other innovations might be needed to prevent water ice accretion in the intercooler.

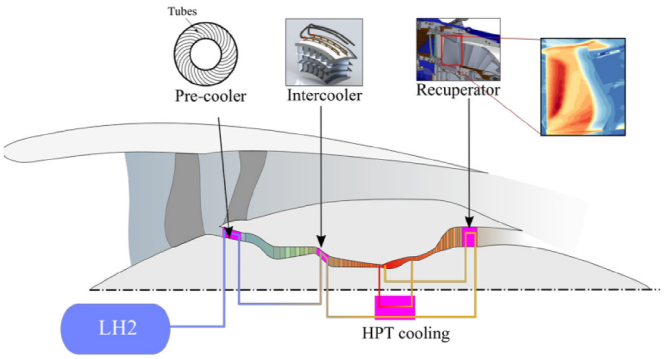


Fig. 14. Fuel heat management systems proposed in ENABLEH2 [42].

3.10. FlyZero

The FlyZero project [16], led by the UK government funded Aerospace Technology Institute (ATI) was a groundbreaking step towards achieving zero-carbon emission commercial aviation [52]. The project analyzed three aircraft concepts for regional, narrowbody and medium-size applications, as illustrated in Fig. 16.

The more detailed FlyZero technical reports covering the fuel and thermal management systems are not publicly available. Publicly available reports cover aircraft concepts, research challenges, and development roadmaps [17,53–57]. Reference [58] summarizes the conclusions from the studies.

The research compared different energy sources with potential for zero carbon emissions, such as batteries, hydrogen, and ammonia, to determine the most viable option to power commercial aircraft. The study concluded that LH_2 was the most feasible option, capable of powering aircraft using fuel cells, gas turbines, and hybrid systems. The technology had the potential to aid aviation achieve net-zero carbon emissions by 2050.

The midsize study aircraft developed in FlyZero could reach any destination worldwide with just one stop, potentially minimizing the commercial risks associated with developing a narrowbody aircraft first. FlyZero's analysis concluded that a mid-sized aircraft could efficiently serve 93% of existing long-haul scheduled flights, enabling infrastructure development to focus on a small number of larger international hub airports.

Fly Zero anticipated that LH_2 would become a more cost-effective and environmentally friendly alternative to 'Power to Liquid' SAF by the mid-2030s as its production increases in order to achieve zero-emission flight. However, the project concluded that revolutionary technological advancements would be needed in six key areas: hydrogen fuel systems and storage, hydrogen gas turbines, hydrogen fuel cells, electrical propulsion systems, aerodynamic structures, and thermal management.

3.11. HySIITE

The HySIITE (Hydrogen Steam Injected Intercooled Turbine Engine) project, led by Pratt & Whitney [59], aimed at developing a high-efficiency, hydrogen-powered turbomachine for commercial aviation. This project is particularly significant as it aims to eliminate carbon emissions and significantly reduce NOx emissions during flight in commercial aircraft. The proposed engine architecture is shown in Fig. 17.

A brief analysis of the HySIITE configuration is provided in Ref. [60]. The engine uses the cold hydrogen to condense water vapor from the exhaust gas. The water is transformed into steam and injected into the intercooler and combustor after exchanging heat with other components. Steam injection reduces the flame temperature and reduces NOx emissions. The LH_2 is heated by the exhaust gas prior to injection into the combustion chamber [61]. Many benefits are claimed, including improvements in cycle efficiency and power, NOx reduction, and cooling effects.

However, the challenges include the complexity and cost of the system, control strategy and material oxidization. As with the FlyZero project, there is no publicly available detailed analysis of the engine architecture or of the study results.

4. Recent patent applications regarding GT LH_2 fuel systems

In addition to the reports and papers mentioned above, the authors

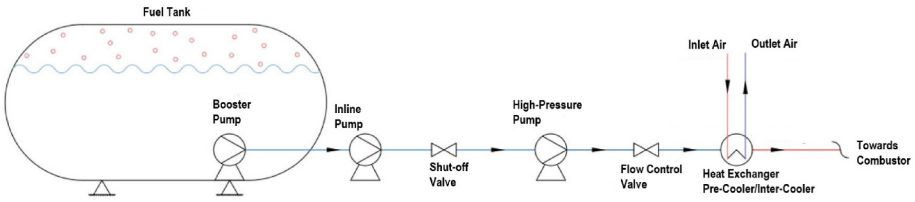


Fig. 15. Fuel distribution system proposed in ENABLEH2 [42].

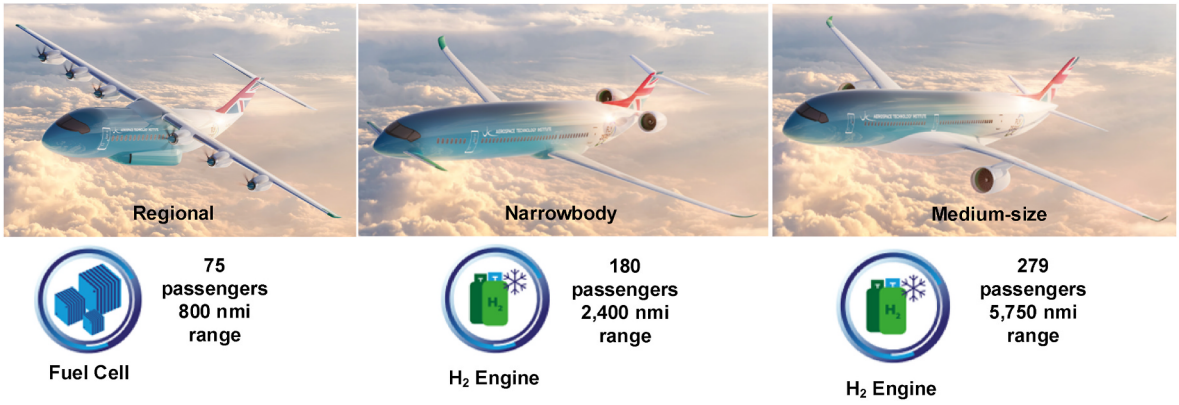


Fig. 16. FlyZero aircraft concepts [16].

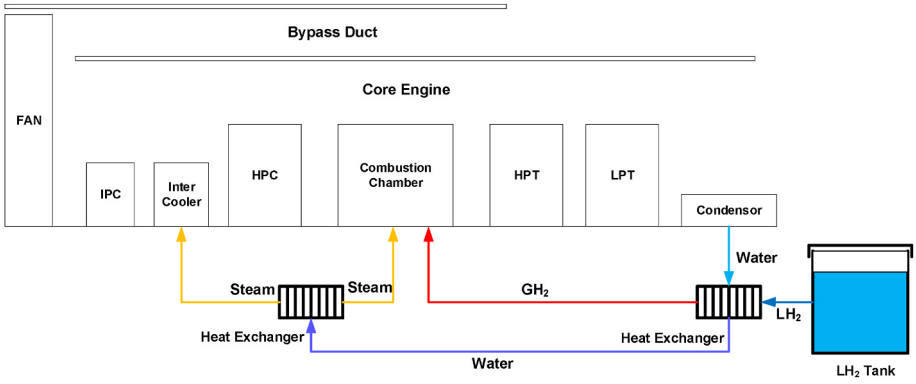


Fig. 17. Pratt & Whitney HySIITE concept, adapted from [61].

have investigated patent filings relating to liquid hydrogen fuel systems, especially for gas turbine engines in aircraft applications. Using the Lens database [62] and proper keywords ('liquid hydrogen', 'aircraft', 'gas turbine'), over 200 patents and patent applications were found, from 1976 onwards. Most of these patents were filed by General Electric, Rolls-Royce, Pratt & Whitney, and RTX (the parent company of Pratt & Whitney).

The overall trend for patent filings is quite similar to that presented for academic papers in Fig. 3. Due to recent technological advances, modifications have been made to systems described in previous patents. For this reason, the analysis concentrates on filings from 2020 onwards. The focus is further limited to those patent applications, and recently granted patents, that relate to engine fuel system architectures. Those relating to the detail design of fuel system components are discounted as falling outside the scope of this examination, as are most non-US and equivalent patent applications. 15 patents are identified as establishing milestones.

Different methodologies and trends can be observed between the various companies. Common features for the leading companies are using hydrogen as a heat sink in the engine cycle, and integrating multiple heat exchangers (e.g., intercoolers and recuperators) in fuel systems. These can be beneficial for engine performance by cooling the air, oil, and electrical systems, and heating the hydrogen before injection into the combustion chamber. Some further comments on the advantages and disadvantages of the highlighted patent applications are included in the discussion section.

4.1. US2024/0132227A1, Rolls-Royce plc, Application published in 2024 [63]

The fuel system for a geared turbofan includes a vaporizer to convert liquid hydrogen fuel into a supercritical or gaseous state for pumping and has a heater downstream of a main pump to raise the temperature of the fuel to its delivery temperature. Two options are compared, either heating the hydrogen from 23 K to 132 K at 4 bar and pumping it to 70 bar, or heating the hydrogen from 23 K to 32 K at 4 bar, pumping it to 70 bar, and heating it again to an injection temperature of 300 K. The latter option reduces the required pumping work.

It is generally more efficient to pump fuel in the liquid state rather than as a gas, but pumping liquid hydrogen is challenging because of

complications in lubricating bearings at such low temperatures, and liquid hydrogen pumps tend to have unacceptably short operating lives. Therefore, a main pump is configured to pump the fuel in the gaseous or supercritical state. To improve temperature control of the incoming hydrogen, an electric heater is used instead of a heat exchanger.

4.2. US12006871B2, Rolls-Royce plc, granted in 2024 [64]

This patent describes a geared turbofan that operates on a complex cycle, utilizing a core gas turbine and a recuperator to heat hydrogen fuel before combustion. The recuperator is a spiral-wound recuperator, which reduces the likelihood of fracture due to thermal expansion and contraction.

The metering device features a sonic fixed orifice designed to operate in a choked condition, with flow rate controlled by adjusting pressure based on the upstream temperature and orifice area. To keep the orifice choked, its exit has a sharp edge.

The fuel heating system includes a vaporizer with a fuel offtake for diverting approximately one per cent of hydrogen fuel for combustion in a separate burner. This allows for controlled pre-heating of the hydrogen fuel by heat transfer.

At certain points in the operational envelope (e.g. at engine start or other cold conditions), there may be insufficient heat output from the engine to raise the fuel temperature to the injection temperature for the separate burner. So the vaporizer includes a small electric heater to ensure the vaporization of the diverted hydrogen fuel prior to it being mixed with air for combustion.

4.3. US2023/0092811A1, Rolls-Royce plc, granted in 2023 [65]

The fuel system is for a geared turbofan engine. An onboard system is proposed for generating inert gas, particularly nitrogen, using a porous membrane nitrogen generator and catalytic air separator. By generating the inert gas onboard, the system reduces reliance on ground-based supplies, enhancing operational flexibility and readiness.

A buffer tank is used to stabilize the hydrogen pressure and ensure a steady supply of hydrogen in startup, shutdown, and unusual transient conditions.

A two-stage purging process is introduced. Firstly using an inert gas, such as nitrogen, to purge oxygen from the fuel lines to avoid explosive mixtures. Secondly, after purging with an inert gas, hydrogen gas is used to flush out the inert gas from the fuel lines, ensuring that the lines are filled with hydrogen gas before introducing liquid hydrogen.

Detailed procedures are proposed for starting and shutting down an engine. For starting, first the valves downstream of the pump are opened. Then, the valve upstream of the pump is gradually opened, and the fuel pump is activated. After ignition occurs, a control valve upstream of the recuperator is opened.

To shut-down the engine, the liquid fuel valve upstream of the pump and the fuel cut-off valve upstream of the combustor are first closed. Then, the liquid fuel pump is shut down. The pressure is managed by modulating the pressure relief valve on the buffer tank, and the vaporizer is turned off when the pressure in the fuel lines matches the buffer tank pressure. For ventilation, the valve closest to the engine is closed, vent valves are opened to release residual gases, and the pressure relief valve is modulated until pressure reaches a safe level.

4.4. US2023/0406527A1, Airbus operations Ltd., Application published in 2023 [66]

A hydrogen fuel line is designed to be rigidly continuous and substantially unconstrained along its axial direction. This means it is uninterrupted by traditional axial compensators, bellows, or other mechanisms used for handling significant axial displacements. The design allows for axial movement at one or both ends of the fuel line to compensate for loads and thermal expansion. It avoids needing multiple couplings and compensators, which are common sources of leaks and complexity in traditional fuel systems.

The hydrogen fuel line has an inner pipe for conveying liquid hydrogen and an outer pipe that surrounds the inner pipe and conveys gaseous hydrogen. The outer pipe provides thermal isolation for the inner pipe by using cold gaseous hydrogen as an intermediate layer.

4.5. US11885260B2, RTX Corporation, granted in 2024 [67]

A turbofan engine has dual fuel supply lines incorporating heat exchangers. A first fuel supply line features a waste-heat recovery heat exchanger (near to the core nozzle) and a second fuel supply line contains an intercooler between the low-pressure and high-pressure compressors. The fuel management system is designed to regulate fuel flow based on different flight phases. In take-off and climb, the controller directs the fuel through the intercooler, enabling increased thrust. At cruise, the fuel is directed through the waste-heat recovery heat exchanger, increasing thermal efficiency.

An expansion turbine has been added to the system to receive preheated hydrogen fuel from the core flow path heat exchangers and to produce mechanical power.

4.6. US2023/0322396A1, RTX Corporation, granted in 2023 [68]

A turbofan engine has a steam cycle incorporated to enhance engine performance. Water is condensed from the exhaust using a condenser downstream of the low-pressure turbine and stored. It is then evaporated to generate steam. Steam is injected into the main flow path to increase turbine mass flow rate and available power.

Water injection is done upstream of the combustion chamber and at turbine stages, providing an intercooling effect and additional cooling. This reduces the size and weight of traditional evaporators and condensers.

A hydrogen expansion turbine is used to expand the preheated hydrogen, to generate power and manage the hydrogen pressure and temperature before the combustion chamber.

4.7. US11754021B2, RTX Corporation, granted in 2023 [69]

This patent proposes using supercritical CO_2 (S–CO_2) as the working fluid in a closed-loop configuration since it can operate at higher temperatures, pressures and density than most other gasses. The S–CO_2 is circulated through the turbine, cooler heat exchanger, and compressor.

Unlike conventional gas turbines, the turbine is not directly driven by the combustion products. The combustion chamber provides the energy to be transferred via a recovery heat exchanger to the S–CO_2, and then the heated S–CO_2 is expanded to drive the turbine that powers the compressor and a fan for propulsion, optionally via a gearbox. Various fuels may be used, but a cryogenic fuel like hydrogen is beneficial in providing a heat sink for the cooler heat exchanger.

The system uses three different heat exchanger configurations:

1) The recuperator heat exchanger, located between the turbine and cooler heat exchanger, recovers heat within the closed-loop system.
2) The cooler heat exchanger can be configured as either an air-to-supercritical fluid or as a fuel-to-supercritical fluid exchanger.
3) The heat recovery heat exchanger utilizes the combusted fuel to heat the supercritical fluid.

There is also the option of compressing the cold hydrogen before it is heated and then expanding it in a turbine to generate some additional net power prior to its combustion.

4.8. US11686222B2, Pratt & Whitney Corp., granted in 2023 [70]

The engine has a water recovery system including a water vapor

collector downstream of the turbine, a condenser (to transform the water vapor into liquid water), and water collectors (to store the condensed water for reuse within the system).

The water recovery system was used for:

1) Cooling engine components.
2) NOx suppression (by managing combustor temperature).
3) Heating-up the liquid hydrogen into the gaseous phase.

The patent also proposed using a gaseous hydrogen accumulator connected to the fuel lines to serve as a high pressure reservoir to store gas for the combustor when needed.

4.9. US2023/0036266A1, Pratt & Whitney Corp., Application published in 2023 [71]

The fuel control strategy is to determine whether the fuel flow is sonic or subsonic by calculating the ratio of the downstream pressure (P2) to the upstream pressure (P1). Based on the fuel state, the controller calculates the required fuel flow and adjusts the metering valve.

For sonic flow ($P2/P1 < 0.5283$), the system calculates the flow rate as a function of the pressure upstream of the metering valve and the upstream fuel temperature (T1). For subsonic flow ($P2/P1 \geq 0.5283$), it calculates the flow rate based on the upstream pressure (P1), the pressure downstream of the metering valve (P2), fuel temperature (T1), and the pressure differential (ΔP), where delta pressure was the pressure difference between the pressure downstream of the metering valve and the combustor pressure.

A dynamic system is described as capable of adapting on the fly to changes in fuel pressure, temperature, and flow conditions. It is smoothly able to manage the transition from subsonic to sonic flow conditions.

4.10. US2023/0375136A1, zero emissions aerospace Ltd., Application published in 2023 [72]

The proposed system had two heat transfer circuits. A primary circuit heats the gaseous hydrogen fuel to the desired temperature, and a secondary circuit transfers heat to the liquid fuel to vaporize it.

It uses a selector device that switches the helium heat-transfer working fluid between the primary and secondary circuits based on the requirements. This ensures that heat is applied where and when it is needed. So, for the warming configuration, the selector device directs helium through the primary heat circuit (just warming the gaseous hydrogen to the desired temperature). For the vaporizing configuration, the selector device allows helium to flow through both primary and secondary heat transfer circuits (when the gaseous pressure zone drops below a certain threshold). The selector device is controlled passively (using an actuated valve) and also actively (using sensors and a programmable controller). The helium may be used for cooling various systems, obtaining heat from those sources and/or an electric heater.

4.11. US2024/0159193A1, General Electric (US)., Application published in 2024 [73]

The proposal is to have dual control systems. The main control system, the Electronic Engine Control System (EECS), monitors and manages general engine operating parameters. The Electronic Combustion Control System (ECCS) is a secondary control system dedicated to hydrogen-specific parameters. It operates with a faster response time of 10 ms or less, allowing precise and fast control of hydrogen's unique properties. It enables rapid ignition control and purging.

The ECCS operates independently from the EECS, allowing it to focus on hydrogen-specific tasks without being affected by the broader control requirements of the entire engine system.

4.12. US2024/0110524A1, General Electric (US)., Application published in 2024 [74]

The exemplary fuel system arrangement uses high-pressure gaseous hydrogen tanks, which may store hydrogen at pressures up to 1000 bar in order to reduce the tank size for better integration in limited spaces. It describes a hydrogen fuel storage system where liquid and gas phases are separately stored in multiple tanks.

This fuel system regulates hydrogen flow through heat exchangers on the engine, bypassing them when appropriate.

However, the specific claims in this patent application relate to the detection of hydrogen leaks and subsequent control actions, including increasing the ventilation of aircraft and engine nacelle compartments and halting the hydrogen fuel flows where necessary.

4.13. US2024/0151358A1, General Electric (US)., Application published in 2024 [75]

The system connects multiple LH_2 tanks via vacuum-jacketed pipelines to function as a single integrated unit. It means that tanks could be refilled simultaneously through a single refueling and extraction flowline, simplifying refueling procedures. The tanks are connected to each other both in parallel and in series.

The fuel system maintains a consistent fuel level (trimmed) among all tanks to prevent aircraft instability.

Phase separator pump systems separate the gas and liquid hydrogen from the flowline to redirect gas to the tank for the pressurization, to reduce the use of vapor pressure regulation systems. It ensures that vapor bubbles do not enter the LH_2 flow line, preventing cavitation, which is critical for the pump operation.

4.14. US2023/0392551A1, General Electric (US)., Application published in 2023 [76]

Cryo-compressed hydrogen (CcH2) storage is proposed as an improvement over LH_2 tanks by combining the benefits of LH_2 and gaseous hydrogen storage. The CcH2 tank is designed to store hydrogen at cryogenic temperatures (40–70 K) and high pressures (up to 100 bar). Using CcH2 tanks eliminates the need for cryogenic pumps (since it would be a pressure-driven fuel system), simplifying the system.

It was further suggested to use compressed natural gas (CNG) in combination with both CcH2 and gaseous hydrogen for operational flexibility. For example, the system utilizes CNG for the engine startup phase and switches to hydrogen for the remaining operational conditions. This approach was chosen because CNG could be used without requiring extreme cryogenic conditions.

4.15. FR3120394B1, Safran., granted in 2024 [77]

The proposed system utilizes isochoric (constant volume) compression instead of mechanical pumps for pressurization. This approach reduces the number of moving parts and energy consumption. The method takes advantage of available heat sources within the aircraft to raise the fuel temperature and thereby to increase the fuel pressure.

The system also included pressure balancing and degassing processes to ensure its safety and stability. For pressure balancing, the fuel is drawn from the cryogenic tank and sent to other tanks for conditioning. Nitrogen, as the inert gas, can be introduced into the cryogenic or other tanks to regulate the pressure. For the degassing process, nitrogen can be used to dilute the gaseous fuel before it is vented or returned to the cryogenic tank.

5. Discussion on LH_2 fuel systems

The current body of research into liquid hydrogen propulsion for aircraft applications underscores a growing interest in its technological

progression. The exploration of various fuel system architectures yields valuable insights into the design space, outlining multiple configurations that could be adopted in future LH_2 fuel systems. The reviewed studies highlight several critical considerations:

A departure from traditional fuel system practices is necessitated by the unique properties of LH_2. For example, there is a consensus that it is necessary to maintain a positive pressure differential within LH_2 tanks to prevent atmospheric air from ever entering and freezing within the system. The selection of tank operating pressure involves a delicate balance. Lower storage pressures favour reduced weight, but introduce two-phase-flow complexities. Supercritical storage pressures ensure single-phase flow, but are generally discouraged due to increased tank weight and more ground complex operations at high pressure [49,54].

The aviation industry's shift away from using helium for tank pressurization, due to cost and sustainability concerns, has led to consideration of alternative methods, such as the injection of superheated gaseous hydrogen, which is supported in recent studies [16,39]. Hydrogen may be heated by ambient air, or sent back to the tanks, either from an engine or from a fuel cell system.

The selection and arrangement of components within the LH_2 fuel system is a critical area of investigation. For example, whether booster pumps should be located internally or externally to the tank, may be determined by considering maintenance requirements and performance objectives. An external location, possibly in a dedicated 'coldbox' [78] may provide easier maintenance access, while an internal location may provide better functionality.

Active cooling systems, such as the Integrated Refrigeration and Storage (IRAS) system proposed by NASA [24,79] could minimize boil-off and LH_2 loss in operation. Although IRAS meets the zero boiloff objective, its reliance on helium as a refrigerant may present challenges, and including this system will increase overall fuel system weight.

Leveraging cryogenic hydrogen as a heat sink could significantly enhance engine performance, but realizing this requires comprehensive system-level development, including aerothermal and design optimization of heat exchanger matrices to mitigate potential risks associated with hydrogen seepage and ignition [43].

Because of the hydrogen phase change, some components will work in the liquid phase, some in the gaseous, and some others in the two-phase regime. The position where the phase change occurs will depend on the system architecture, boundary conditions, operating conditions, and ambient conditions. The phase change affects the fuel density and other characteristics, driving the control system requirements [80]. Sophisticated control systems will need to be designed and developed to deal with phase changes and to guarantee the safe and reliable operation of the fuel system.

Due to the lack of experimental data and low technology readiness level (TRL) for liquid hydrogen systems, more comprehensive and higher fidelity models should be developed. Component-level development is also needed for LH_2 fuel and thermal management systems. For example, due to the two-phase behavior of hydrogen in the fuel system, cavitation is likely to occur in fuel pumps, which may degrade their functionality [81]. Heat exchangers that work directly with hydrogen will need innovative designs to minimize pressure loss and avoid icing problems [43].

The ortho-para hydrogen equilibrium is a crucial factor in both the liquefaction and evaporation of liquid hydrogen. Failing to account for this equilibrium can introduce technical challenges, reduce system efficiency, and compromise storage stability [82]. One solution to address this issue involves the use of catalysts during the liquefaction process to accelerate the conversion process [83,84]. Without any catalysts, the conversion might take hundreds of hours [85]. Therefore, following liquefaction at cryogenic temperatures, it is generally assumed that LH_2 exists primarily in the para-hydrogen state.

In cryo-compressed hydrogen storage, hydrogen is typically stored at pressures ranging from 50 to 700 bar and temperatures between 25 K and 110 K [86]. This method offers several advantages, including a higher volumetric energy density, maintenance of a single-phase fluid, and reduced boil-off losses. However, liquid hydrogen storage also presents significant benefits, such as a higher gravimetric energy density, technological maturity, and a relatively simple tank design [19,20]. The optimal storage method depends on a balance of trade-offs, considering mission requirements, aircraft design, safety, and cost constraints.

Challenges such as excessive or rapid injection of warm GH_2 for pressurization, insufficient insulation, and suboptimal system architecture can exacerbate evaporation losses, thereby reducing the available LH_2 for the mission [39,87]. Proposed solutions to mitigate these issues include: (1) employing an efficient tank pressure control strategy and actuation systems, (2) utilizing Multi-Layer Insulation (MLI), (3) efficiently managing heat sinks and sources within the engine and aircraft to ensure effective heating and cooling of critical components, and (4) incorporating onboard cryocoolers to re-liquefy evaporated hydrogen.

Based on recent patent filings, major engine companies have proposed various technical solutions, including:

- A cryogenic pump operation methodology to reduce the pump size and meet the engine demand.
- Heat exchanger configurations for novel thermodynamic cycles to enhance efficiency, including steam injected cycles and closed-loop cycles using supercritical CO_2 or helium.
- Multiple fuel line integration: using cryocooled compressed hydrogen and compressed natural gas tanks or dual phase saturated hydrogen tanks, and on-board inert gas production to enhance the operational flexibility of the aircraft (by injecting each type of fuel based on the operating point).
- A fuel offtake with a vaporizer for diverting hydrogen fuel for combustion in a burner and ensuring that the hydrogen fuel is in the correct phase for efficient combustion.
- An engine combustion control system that operates independently from the engine control system to manage the unique characteristics of hydrogen more quickly and precisely.
- Implementing new sensor integration methods to manage the fuel state and a smooth transition between sonic and subsonic conditions.
- A selector device to switch between warming and vaporizing hydrogen for the storage system when needed to utilize the waste heat from the cycle efficiency and to avoid over-pressure conditions.
- Continuous hydrogen fuel lines and integrated storage systems to reduce system complexity and potential leakage points, improving aircraft safety and stability.
- Using isochoric (constant volume) compression instead of mechanical pumps for pressurization.

However, these technological advancements come with challenges. For example: using dual fuel supply lines (especially if utilizing other fuels as well as hydrogen) and sophisticated fuel metering systems to manage fuel flows in different phases of flight will add further complexity to the fuel control and management systems. Systems relying on complex cycles, auxiliary cooling, or waste heat recovery, must be developed to operate properly in less favorable conditions. Improving the gravimetric efficiency for hydrogen storage at very high pressures will require significant investment and materials development.

A summary of critical literature on hydrogen fuel systems in aircraft applications for gas turbine engines is given in Fig. 18, and a progress pathway is presented in Fig. 19. A summary of proposed LH_2 fuel system architectures, and specifications is presented in Table 1.

6. Conclusions

This paper has reviewed proposed fuel system architectures for liquid hydrogen-powered gas turbine engines. Current studies demonstrate a huge interest in the technological advancement of aircraft propulsion using LH_2. Various studies have proposed fuel system

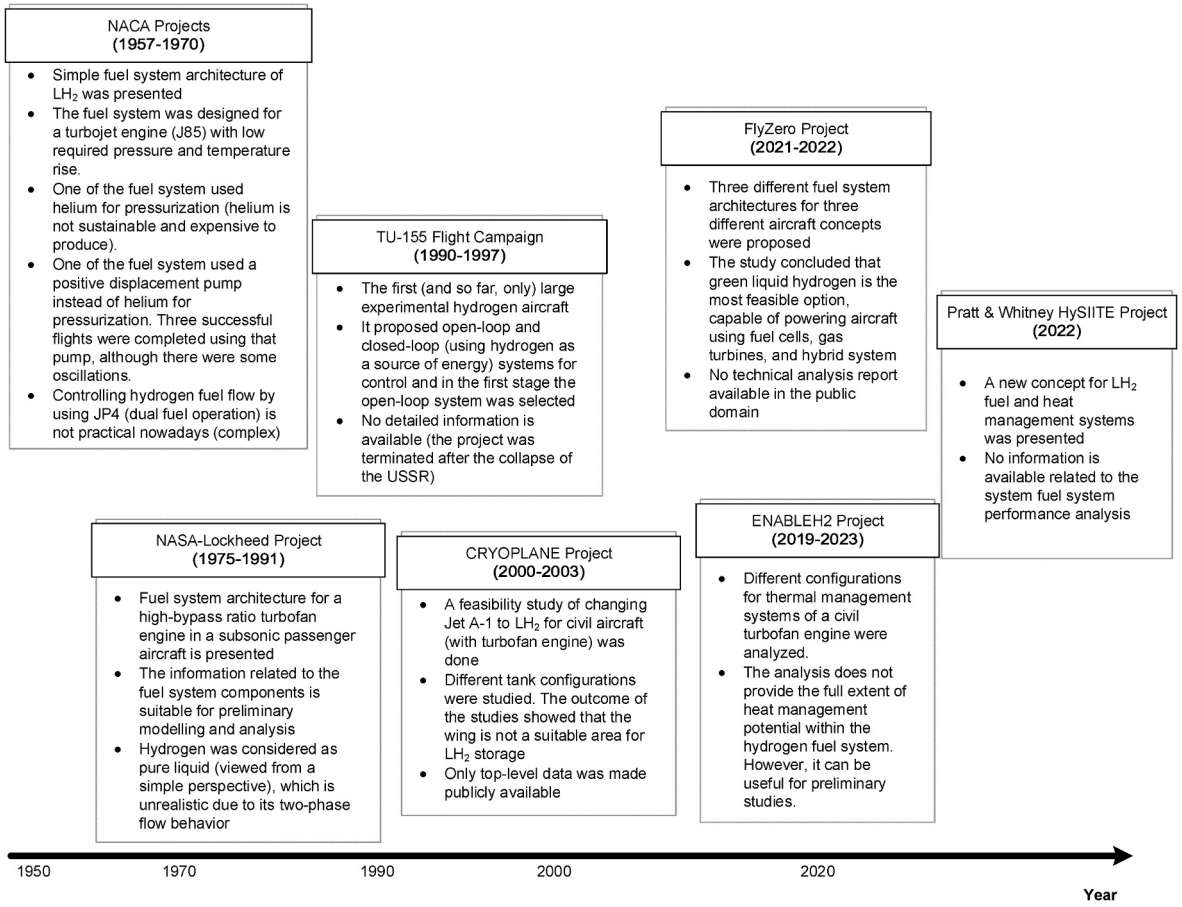


Fig. 18. Summary of major projects, including liquid hydrogen-powered aircraft engines.

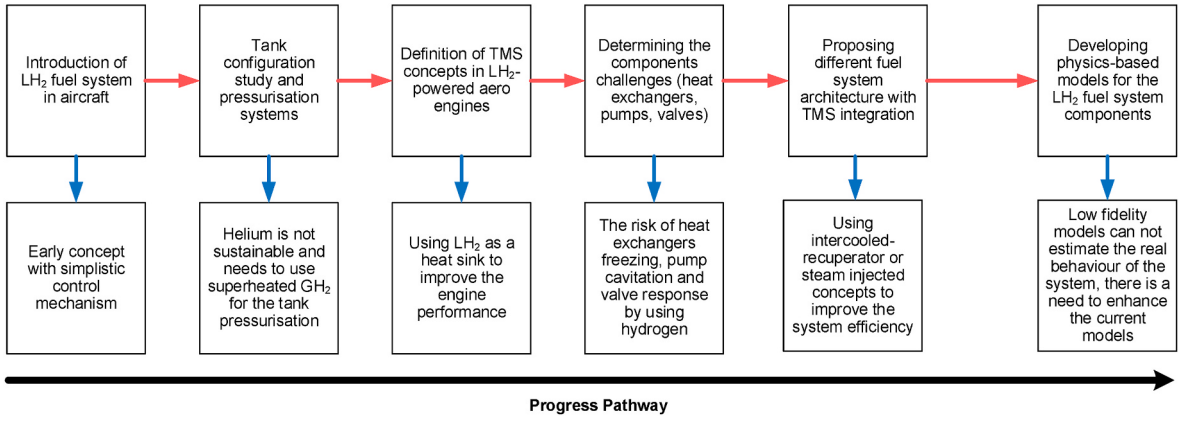


Fig. 19. Progression in liquid hydrogen fuel system concepts for aircraft engines.

architectures that provide insights into potential design spaces and raise questions that can guide future research.

6.1. System-level development

Utilizing LH_2 as a heat sink in thermal management systems can enhance engine performance. However, it is necessary to explore the aerothermal optimization of the heat exchanger matrices to fully harness the potential of hydrogen as a heat sink while minimizing pressure losses, weight and volume.

The selection and arrangement of components within the LH_2 fuel system remain critical areas for investigation. For instance, the strategic placement of booster pumps, either within or adjacent to the fuel tanks, should be informed by a balance of maintenance demands and performance criteria. Integration of innovative systems and mechanisms, such as active cooling, is essential to mitigate boil-off and reduce LH_2 loss during fuel system operations.

System architects will also need to assess the design challenges relating to cost and weight.

6.2. Component-level development

Addressing two-phase behavior of hydrogen within the fuel system is paramount, as it can induce cavitation in fuel pumps, impairing their

Table 1
LH_2 fuel systems specification (based on the literature review).

Source/Authors	Otto et al. Mulholand et al.	Fenn et al.	Goldsmith et al.	Brewer et al.	Simon, Brines, and Orlov	Pohl and Malychev	CRYOPLANE Final Report	ENABLEH2 Public Reports	ATI FlyZero Public Reports	HySIITE articles and Wang et al.
Year	1957	1960	1973	1975–91	1994	1990–97	2003	2019–23	2021	2022–24
Funder/Project lead	NACA	NACA	NASA	NASA	MTU	USSR	Airbus	EC	ATI	US DoE
References	28, 33	34	35	37–39	46	47, 48	49, 50	41–43	53–58	59–61
Aircraft	B-57	B-57	B-57	–	A310	TU-155	A310	–	–	–
Engine model	J65	J65	J85	–	JT9D	NK-88	JT9D	–	–	–
Engine type	Turbojet	Turbojet	Turbojet	Turbofan	Turbofan	Turbofan	Turbofan	Turbofan	Turbofan	Turbofan
Realization (study, ground run or flight test)	Flight	Flight	Ground	Studies	Studies	Flight	Studies	Studies	Studies	Studies
Helium pressurization	Yes	No	Yes	No	–	Option	–	No	No	–
Nitrogen purge system	Yes	No	Yes	–	–	Yes	–	–	–	–
Tank normal max operating pressure barA	–	–	2.06	1.52	–	–	≪13	1.6	–	–
Tank normal max operating pressure barG	3.44	–	–	–	–	–	–	–	–	–
LH_2 LP boost pump discharged pressure barA	None	3.65	None	4.62	–	–	–	4.1	–	–
LH_2 LP pump type	NA	Recip.	NA	Turbo	–	–	Turbo	–	–	–
Maximum hydrogen temperature K	61	61	144	677	–	–	250	670	–	–
Ullage gas boost pump	None	None	None	None	–	–	None	–	–	–
Air/fuel preheater	Yes	Yes	Yes	–	–	–	–	–	–	–
Intermediate inline pump	No	No	–	–	–	–	–	Option	–	–
HP pump maximum pressure rise barA	NA	–	32.5	46.9	–	37	–	44	–	–
HP pump type	–	–	Recip.	Turbo	–	Turbo	Turbo	–	–	–
Fuel back to tanks system	No	No	No	Yes	–	No	–	–	Yes	–
Turbine cooling air heat exchanger	No	No	No	Yes	No	Option	–	Yes	–	Yes
Fuel/Oil heat exchanger	No	No	No	Yes	Yes	No	–	–	Yes	–
ECS heat exchanger	No	No	No	Yes	No	No	–	No	No	No
Turbine exhaust heat exchanger	No	No	No	Yes	Yes	Yes	–	Yes	–	–
Water condenser and steam generator	No	No	No	No	No	No	No	No	No	Yes
Intercooler or aftercooler	No	No	No	Option	Option	Option	–	Option	No	Yes
Hydrogen-driven turbine	No	No	No	Option	Option	Option	–	Option	–	–
Features that are less relevant to the engine's H2 fuel system										
Other fuel (in addition to, or alternative to H2)	JP-4	JP-4	LNG	None	–	Jet/LNG	–	–	–	–
Subcooler before boost pump	–	–	Yes	–	–	–	–	–	–	–
Vacuum-insulated tanks	No	No	No	–	–	–	–	–	Option	–
Foam-insulated tanks	Yes	Yes	–	–	–	–	–	Yes	Option	–
Routine ullage gas venting	Yes	Yes	Yes	–	–	–	–	No	No	–
Number of LP pumps per fuel tank	0	1	0	3	–	–	3	–	–	–

functionality. Moreover, the design of hydrogen-compatible heat exchangers must overcome challenges such as pressure loss and icing, which can detrimentally impact engine performance.

6.3. Phase-change management

The occurrence of phase changes within the system components, dictated by the architecture, boundary conditions and operational parameters, necessitates the design of control systems to ensure safe and reliable operation. This will require precise measurement of hydrogen states in the aircraft and engine fuel systems.

6.4. Modelling and data acquisition

A pronounced deficiency in experimental data and the low TRL of LH_2 systems underscores the need for more sophisticated and high-fidelity models to address these challenges and to achieve optimal efficiency. The occurrence of phase changes within the system components, dictated by the architecture, boundary conditions and operational parameters, necessitates the design of control systems to ensure safe and reliable operation. This will require precise measurement of hydrogen states in the aircraft and engine fuel systems.

CRediT authorship contribution statement

Alireza Ebrahimi: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Andrew Rolt:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis. **Soheil Jafari:** Writing – review & editing, Methodology, Formal analysis. **Jon Huete Anton:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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A review on liquid hydrogen fuel systems in aircraft applications for gas turbine engines

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