

Enabling Cryogenic Hydrogen-Based CO₂-Free Air Transport

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Flightpath 2050 from the European Union (EU) sets ambitious targets for reducing the emissions from civil aviation that contribute to climate change. Relative to aircraft in service in year 2000, new aircraft in 2050 are to reduce CO₂ emissions by 75% and NO_x emissions by 90% per passenger kilometre flown. While significant improvements in asset management and aircraft and propulsion system efficiency and are foreseen, it is recognised that the Flightpath 2050 targets will not be met with conventional jet fuel. Furthermore, demands are growing for civil aviation to target zero carbon emissions in line with other transportation sectors, rather than relying on offsetting to achieve 'net zero'. A more thorough and rapid greening of the industry is seen to be needed to avoid the potential economic and social damage that would follow from constraining air travel. This requires a paradigm shift in propulsion technologies. Two technologies with potential for radical decarbonisation are hydrogen and electrification. Hydrogen in some form seems an inevitable solution for a fully sustainable aviation future. It may be used directly as a fuel or combined with carbon from DAC (direct air capture of CO₂) or other renewable carbon sources,

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to synthesise drop-in replacement jet fuels for existing aircraft and engines. As a fuel, pure hydrogen can be provided as a compressed gas, but the weight of the storage bottles limits the practical aircraft ranges to just a few times that achievable with battery power. For longer ranges the fuel needs to be stored at lower pressures in much lighter tanks in the form of cryogenic liquid hydrogen (LH₂).

Hybrid/electric/fuel cell technologies seem attractive for short to medium range aircraft, but hydrogen combustion in gas turbines could still be preferred for larger and faster flying aircraft on longer routes. However, the large financial investments required to make these aircraft a reality will not be committed until several technical challenges have been addressed.

Two decades ago, the Airbus-led Cryoplane project was a flagship for LH₂. It concluded that there were no technical showstoppers to its use, but at the time the costs associated with the fuel and its introduction curbed the industry's enthusiasm. Today there is a growing consensus that LH₂ will soon become more affordable than drop-in fuels and the transition costs will be justified considering the huge environmental and socio-economic benefits of sustainable aviation.

Cranfield University is leading the EU Horizon 2020 ENABLEH2 project providing thought leadership to help revitalise enthusiasm for LH₂ in civil aviation. ENABLEH2 is researching key technologies to achieve zero mission-level CO₂ and ultra-low NO_x emissions together with long term safety and sustainability. Project partners include Chalmers University, London South Bank University, Safran, GKN Aerospace, Heathrow Airport Limited, the European Hydrogen Association, ARTTIC and ARTTIC Innovation.

Key technologies being matured through a combination of numerical and experimental research and innovation are:

- Hydrogen micromix combustion for ultra-low NO_x.
- Fuel system thermal management to exploit the formidable cooling potential of LH₂ to enable more efficient aircraft and propulsion technologies.

Dedicated models are being developed to evaluate LH₂-fuelled aircraft with respect to energy efficiency, emissions, lifecycle CO₂ emissions, and operating costs for potential fuel price and emissions-taxation scenarios. The concept aircraft include "max synergy" designs that benefit from electrification. The benefits and economic viability of these LH₂ aircraft will be quantified relative to best-case scenario projections for conventional Jet A-1 (kerosene), biofuels and liquefied natural gas (LNG). Best-practice safety guidelines are being generated for LH₂ at aircraft, airport, and operational level. ENABLEH2 will also deliver comprehensive roadmaps for the introduction of LH₂.

To maximise the technical rigour and impact of the project, ENABLEH2 has an active Industry Advisory Board (IAB). The IAB comprises key civil aviation stakeholders including aircraft and propulsion system OEMs, airlines, energy companies, and industry organisations. IAB members include: Abengoa, ACI, Airbus, Air Liquide, ATI (FlyZero), Clean Sky 2 JU, Dassault Aviation, EASA, easyJet, Gexcon, IAG, HyEnergy, IATA, ICAO, IMI, Infosys, Lufthansa Technik, MHPS, MOOG, MTU, Reaction Engines, Rolls-Royce, Siemens and Total.

Low NOx Hydrogen Combustion

A key challenge for hydrogen-fuelled aero gas turbines is the research, design, and optimisation of hydrogen combustion systems to deliver low NOx emissions. NOx generation strongly depends on combustion temperature and residence time. When coupled with appropriate combustion technologies, the thermal and chemical properties of hydrogen make it an ideal candidate for minimising NOx without performance, operability, or safety compromises:

- Although the maximum (stoichiometric) flame temperature of hydrogen is higher than that of kerosene and most hydrocarbon fuels, it has much wider flammability limits. Combustion at leaner fuel-to-air ratios is therefore possible which results in lower flame temperatures and lower NOx.
- Gaseous fuels are simpler to mix with air than liquid fuels that require atomisation and evaporation. Although hydrogen will be stored as a cryogenic liquid in the fuel tanks, it will be compressed and pre-heated before injection into the combustor as a gas.
- The high molecular diffusivity and reactivity of hydrogen enable higher mixing and reaction rates, reducing the time required for complete combustion. This reduces NOx emissions and enables combustion chambers to be made shorter.
- In the event of a flameout at high altitude, being able to relight an engine is a key safety requirement. Since hydrogen is more easily ignited than existing fuels, hydrogen combustion systems are expected to provide improved altitude relight performance.
- Combustor liner durability improves in the absence of the intense radiation from flames containing carbon.

Hydrogen micromix combustion for aero engines was first studied in the 1990s. The micromix concept uses a very large number of small injectors resulting in many small hydrogen flames burning at very lean conditions. This limits flame temperature and the production of NOx. An illustrative comparison of segments of conventional kerosene and hydrogen micromix annular combustors is shown in Figure 1.

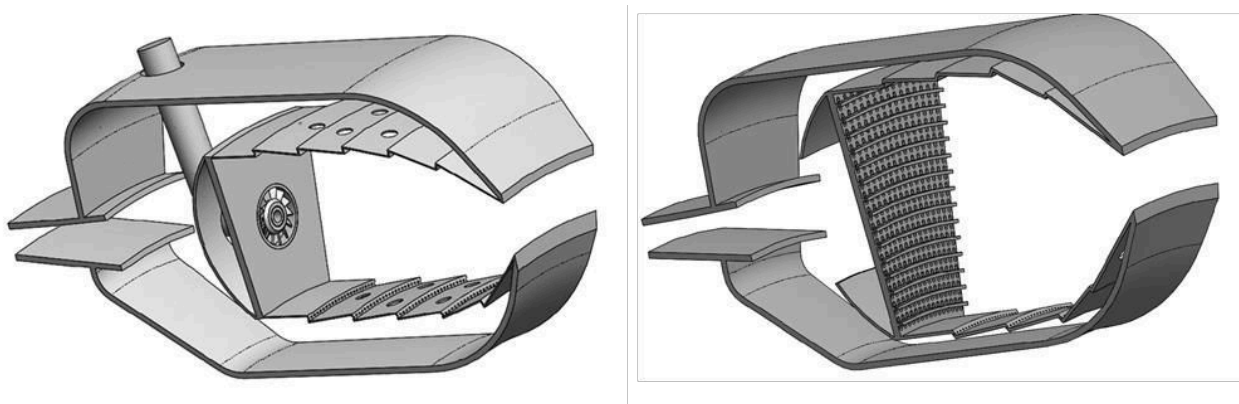


Figure 1- Comparison of conventional kerosene annular combustor (L) and a conceptual hydrogen micromix combustor (R).

Figure 2, shows hydrogen is injected via very small holes into air jets, to provide extremely rapid ‘jet in crossflow’ mixing just upstream of the flames. This reduces the risk of auto-ignition and flashback which is a challenge for most lean combustion systems where the mixing is further upstream. The tiny micromix injectors provide superior fuel and air mixing and faster reaction rates relative to larger injectors.

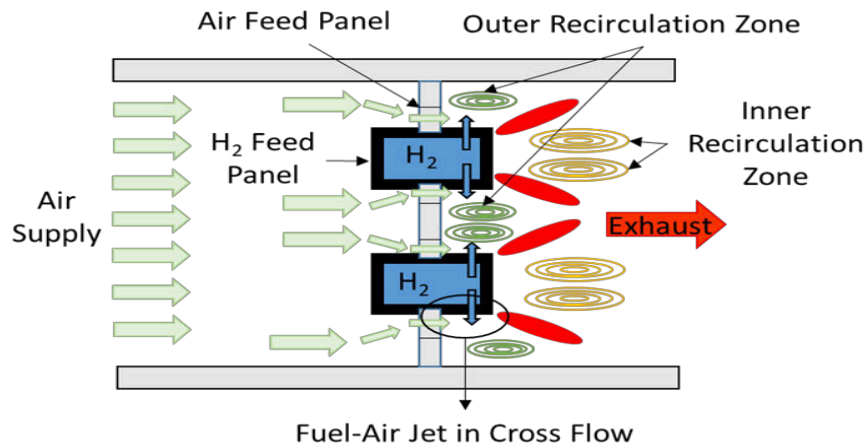


Figure 2- Fuel air jets in crossflow

Hydrogen micromix combustors can offer several extra benefits that extend beyond NO_x reduction. The large number of injectors provides an additional degree of freedom to control the fuel supply to the injector plate, to better control the combustor outlet radial and circumferential temperature profiles. This can benefit combustor and turbine life and performance. Customising the fuel scheduling via micromixing is also expected to better control any combustion thermoacoustic instabilities.

Research into hydrogen micromix combustion within the ENABLEH2 project follows three phases:

Phase 1: Small-scale injector down-selection and test

Phase 1 includes numerical (CFD- Computational Fluid Dynamics) and experimental studies of a small-scale injector array comprising 50 injectors as depicted in Figure 3.

The main objectives

- To assess the characteristics and emissions, for a wide range of operating conditions
- To deliver a detailed understanding of the mixing and reaction of hydrogen and air
- To provide a set of tools using the experimental data

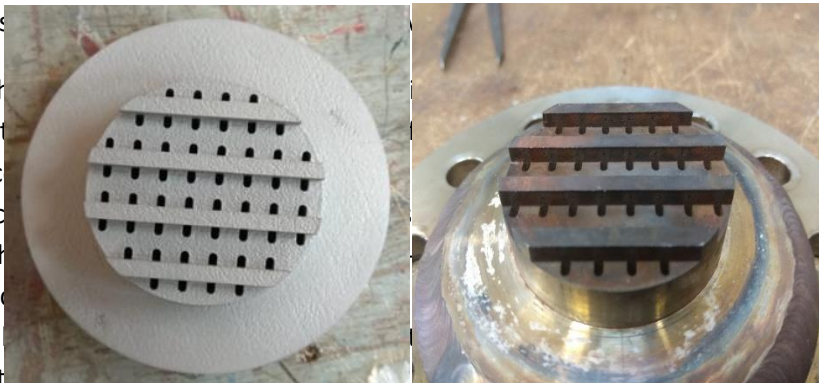


Figure 3- Hydrogen micromix injector prototype.

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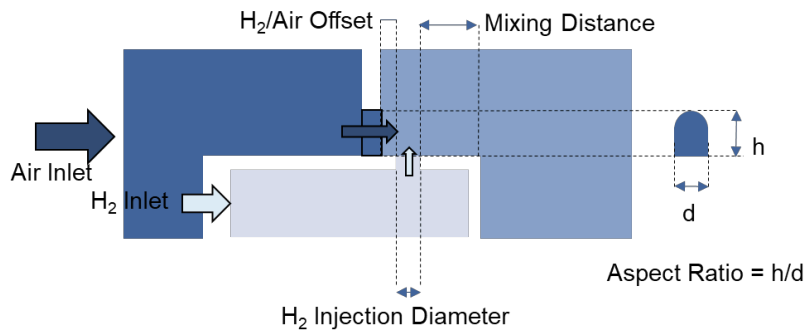


Figure 4- Hydrogen micromix injector design variables.

The numerical studies have shown that changing the values of the injector design variables has a significant impact on the momentum flux ratio of the hydrogen and the air (i.e., the penetration of the hydrogen into the air stream). This significantly affects the flame shape, size, positioning, and flame to flame interactions and consequently the NO_x emissions (as shown in Figure 5).

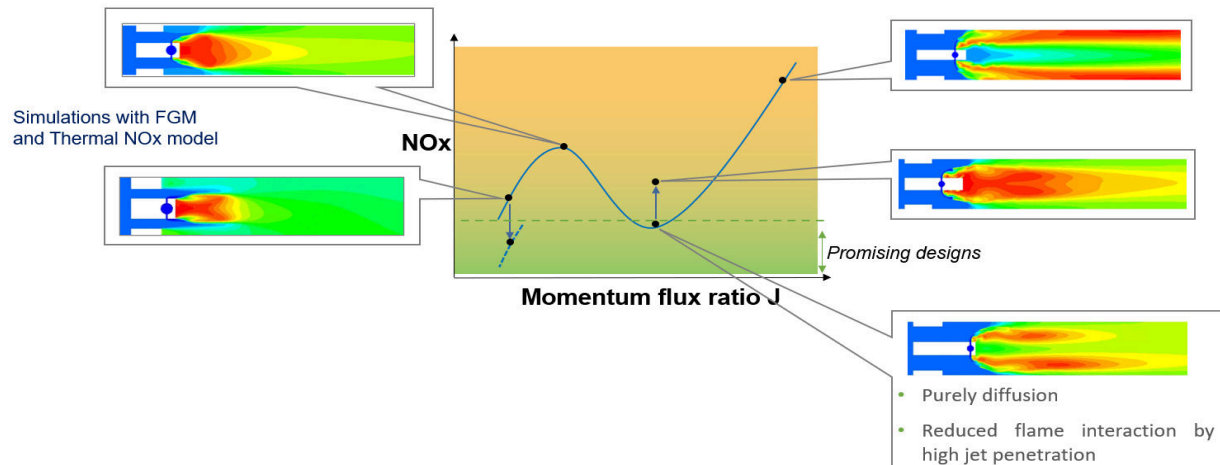
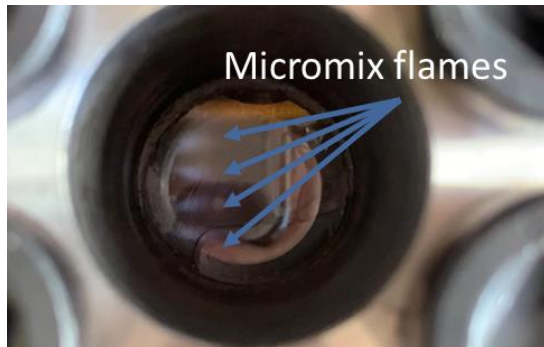


Figure 5- Influence of hydrogen micromix injector design variables on NO_x emissions

For the experimental campaigns in Phase 1 and Phase 2, Cranfield University's pebble bed heater facility is used to provide up to 3 kg/s of air at up to 15 bar pressure and 700 K to achieve representative combustor inlet conditions. The Phase 1 experimental rig is shown in Figure 6



including the combustion chamber and downstream flow measurement and regulating devices. The rig includes optical access windows for hydrogen flame visualisation (Figure 7). All the necessary health and safety protocols have been implemented to allow hydrogen combustion experiments at high temperature and pressure, and the use of laser diagnostic instrumentation for data acquisition. The data being acquired from the experimental campaign are being used to evaluate, validate, and calibrate the CFD models.

The outcome of the Phase 1 study will be to identify suitable injector geometries for the larger-scale Phase 2 studies.

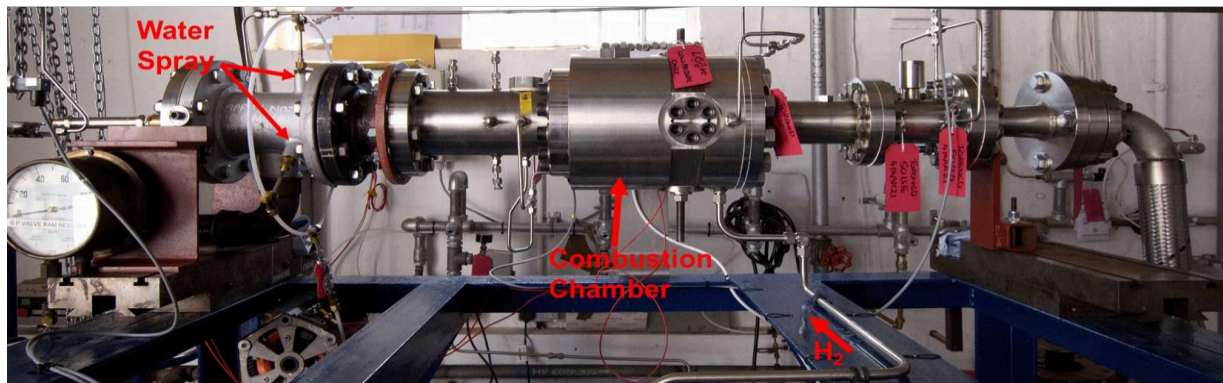


Figure 6- Phase 1 experimental rig.



Figure 7- Optical access window to observe hydrogen micromix combustion.

Phase 2: Annular combustor segment performance assessment and emissions measurement

Phase 2 will combine experimental and complementary CFD numerical studies to:

- Demonstrate that the down-selected injector geometry and injector-array configurations (in Phase 1) can be scaled to full size combustor configurations without compromising NO_x emissions and combustion efficiency.
- Provide proof of concept that the combustor outlet temperature profile and potential combustion instabilities can be controlled by varying fuel scheduling to different parts of the injector array.

Phase 3: Sub-atmospheric altitude relight capability test

Phase 3 will mainly focus on testing the weak extinction and altitude relight of the selected micromix injector at sub-atmospheric conditions, as well as numerically modelling the process. The aim is to determine the limits on conditions for which it is possible to achieve successful ignition and to demonstrate the feasibility of successful relight in the event of a flameout at high altitude.

Hydrogen Combustion Thermoacoustic Instabilities

Combustion instabilities are being investigated via experimental and numerical studies for hydrogen micromix injectors. It is believed that diffusion flames are less prone to thermoacoustic instabilities compared to lean premixed flames. However, hydrogen micromix flames are extremely compact, which might lead to high acoustic amplifications at higher frequencies. In addition, since most of the air entering the combustor is used to achieve lean combustion in micromix combustors, less air is available for combustor cooling and acoustic damping.

Traditionally thermoacoustic analysis has only been performed when targeting high TRL (Technology Readiness Level) relatively late in development programmes. In ENABLEH2, the application of thermoacoustic analysis at lower TRL will ensure that good acoustic design is embodied in the fundamental combustion concept. The objective will be achieved via a thermoacoustic risk assessment of representative combustors under real engine conditions. A roadmap will also be developed for the thermoacoustic assessment and design of a demonstration micromix combustion engine. This will reduce late-stage rig and on-engine testing. It should also reduce remedial design work and the need to incorporate additional acoustic control measures.

Hydrogen Fuel System Thermal Management

In a cryo-fuelled hydrogen engine the fuel system is pushed to the limit. The challenges to operate with the high level of reliability of conventional gas turbine engines are substantial. Fuel tanks require light weight cryo-storage designs with robust insulation technology to provide continuous reliable operation with minimal boiloff. They must use embrittlement-resistant materials that can withstand the detrimental

effects of repeated cyclic temperature variations. Reliable subsystems comprising buffer-tanks, cryo-pumps, shut-off/non-return valves and insulated distribution lines are required to supply the high-pressure supercritical hydrogen fuel flows required for engine operation at different engine settings.

Fuel thermal management is by no means a lesser challenge. The temperature of the cryogenic LH₂ needs to be increased prior to combustion. The optimum amount of pre-heating is subject to conflicting design objectives. To improve heat input for combustion, the heat-management system designer is eager to increase the fuel temperature as much as possible, up to a level that provides diminishing returns in efficiency improvement. The combustion designer is driven to ensure a high combustion efficiency and stable combustion processes, with adequate durability for the fuel injectors and minimal NO_x emissions at critical operating conditions. For instance, when increasing the hydrogen temperature from 25 K to typical compressor outlet temperatures of 800-1000 K, the energy content per kilogram of fuel amounts to about 10% of the fuel heating value. Theoretically, in a loss free system, this alone has the potential to reduce the engine specific fuel consumption by 10%. Losses arising from the installation of a pre-heating system will reduce this benefit, but arguably major gains are still within reach for optimized fuel heat management architectures. Conversely, from the perspective of a combustion system engineer, a 1000 K fuel injection temperature is detrimental to the fuel injector durability and may increase NO_x emissions.

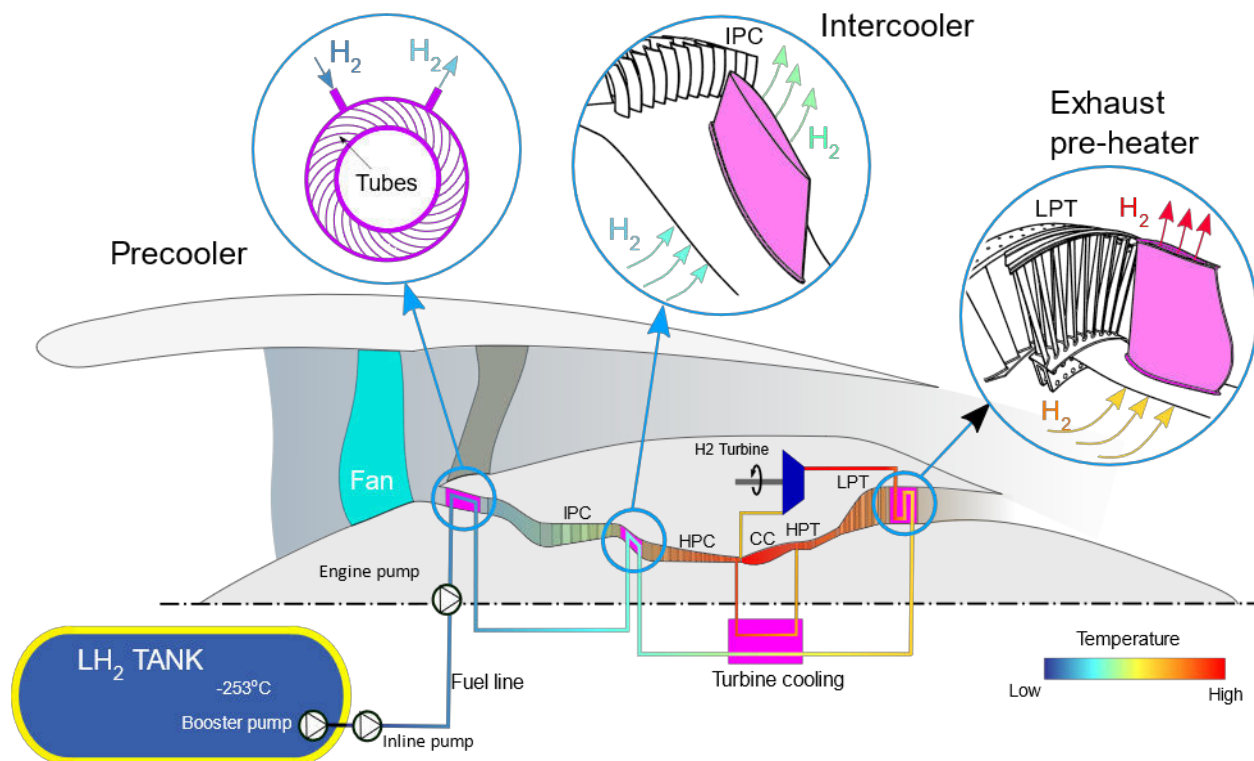


Figure 8-Cross-sectional meridional cut of a turbofan engine, including possible locations for core heat rejection to the hydrogen fuel (in purple). The fuel is stored at its boiling point in the LH₂ tank. The temperature of the hydrogen in the fuel line is increased by the different core installed heat exchangers on its way to the combustion chamber (CC). IPC: Intermediate-pressure compressor; HPC: High-pressure compressor; HPT: High-pressure turbine; LPT: Low-pressure turbine.

The pre-heating of the fuel can be achieved in several ways. In an early successful LH₂ fuelled experimental aircraft programme, a modified J-65 turbojet engine was fed with hydrogen for 21 minutes in cruise conditions. The pre-heating system used a separate ram-air heat-exchanger located in one of the modified B57 aircraft's wings. In the same programme, another concept using compressor bleed air for pre-heating was also successfully tested. Although both options are feasible, neither realizes the potential synergies between fuel heat management and other engine systems. For example, high temperature heat sources in the engine core can be integrated with fuel heat management to maximize the engine efficiency while enhancing component durability. Various heat exchanger concepts to pre-heat the cryo-fuel are illustrated in Figure 8 on a schematic cross section of a modern ultra-high-bypass turbofan engine. The sequence of heat exchangers, from the LH₂ tank to combustion chamber, represents a fuel heat management system. It is noted that this arrangement is only illustrative, and the optimal architecture is subject to a detailed assessment of the integrated performance, including safety and operability aspects at design and off-design conditions.

The air precooler is represented as a tubular involute spiral heat-exchanger, placed in the engine core flow between the fan and intermediate pressure compressor (IPC). The selection of an involute spiral configuration is preliminary, since one of the aims of ENABLEH2 is to evaluate which designs give the best compromise between heat transfer and aerodynamic performances for specific applications. The intercooler is located between the IPC and the high-pressure compressor (HPC). This heat-exchanger is represented here by a cooled compressor-duct vane. These options realize one of the advantages of rejecting heat from the air to the cryogenic hydrogen, as the denser cooled air can be compressed more efficiently. The combination of liquid hydrogen's high specific heat with its cryogenic storage temperature results in fuel with an increased cooling capacity that can be exploited in more compact heat exchanger solutions. This allows the direct use of existing turbomachinery surfaces (vanes, hubs, shrouds, and nozzles) that normally operate in high-speed air flows that increase heat transfer rates. The precooler and intercooler installations also allow for a re-optimized core delivering increased overall pressure ratio (OPR) and core specific power without exceeding engine cycle temperature limits. Another advantage arising from precooling and/or intercooling is the possibility of reducing the combustor inlet temperature for a given OPR, which will also help reduce NO_x emissions.

A challenge with both concepts is the risk of ice formation in the presence of humid air, which might cause a partial or complete blockage of the engine core air flow. This hazard is more critical in the precooler due to the lower temperatures expected at engine core inlet. However, it can be partly alleviated by the introduction of some valves in the fuel system that allow the cold hydrogen to by-pass some heat exchanger elements when icing is a risk.

The high-pressure turbine cooling air may also be cooled with hydrogen (as indicated by turbine cooling in Figure 8). This could improve the engine efficiency by reducing the secondary air flow needed for turbine cooling. The fuel temperature is finally increased by heat exchange with the core nozzle exhaust flow exiting the low-pressure turbine. A tailored heat-exchanger integrated with the outlet guide vane is shown as the exhaust pre-heater for hydrogen in Figure 8) This may be where most of the temperature

rise is provided to the fuel, and it is believed to be an essential component for LH₂ fuelled gas turbine aeroengines.

Integrated performance simulation

In project ENABLEH2, the different heat management architectures are evaluated with respect to their impact on engine performance. Care is taken to qualify the different types of heat exchangers regarding safety and operability at design and off-design conditions. The performance of the different radical core heat exchanger concepts is evaluated using numerical methods implemented within Chalmers' in-house propulsion simulation tool GESTPAN (GEneral Stationary and Transient Propulsion ANalysis). The modelling environment of GESTPAN was extended to include three key features required to model an integrated cryogenic fuel heat management system:

- Inclusion of new combustion products tables to complement conventional kerosene tables normally stored in performance codes.
- The integration of detailed modelling for the heat management system as the cryogenic fuel flows from the tank to the combustor chamber, i.e., hydrogen properties are modelled for every specific point in the fuel distribution and pre-heating process. This also includes the refinement of system level models to better predict the performance when operating with fluids close to the saturation line.
- Means to model and manage heat flows between the fuel system and the propulsion system, i.e., heat transferred from the core to the fuel and vice versa, as such coupling needs to be accounted in the performance assessment.

Detailed design work on both conventional and radical turbomachinery heat rejection surfaces, and evaluations of their aerothermal performance have been carried out in ENABLEH2. Design optimization routines using in-house turbomachinery design tools have been created for the purpose. The routines allow for the design of specific turbomachinery heat rejection concepts based on engine performance (thermodynamic point calculation) requirements and engine design constraints. Their sole purpose is the creation of validated computational models from which aerothermal performance data can be extracted and provided to system-level models in the form of correlations for optimization studies.

New engine core aerothermal facility

The modelling methods are expected to be refined and validated using experimental aerothermal data obtained in compressor and turbine rig facilities at TRL 4. Both facilities are located at the Chalmers University of Technology, Laboratory of Fluid and Thermal Sciences, see Figure 9. The facilities are designed to achieve an accurate low-speed aerothermal representation of state-of-the-art engine components for future engine applications. The engine exhaust fuel pre-heater concepts are investigated in the existing Chalmers' annular semi-closed one and a half stage low-pressure turbine test facility, shown in the lower part of Figure 9. The facility is instrumented for highly accurate heat transfer and flow measurements, where each vane can be independently instrumented for different purposes.

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Instrumentation such as hotwire-anemometry, particle image velocimetry, oil flow visualisation and infra-red (IR) thermography have been successfully implemented. The facility also includes two traverse systems to enable near full-volume 360-degree access for measurements on the engine exhaust flow.

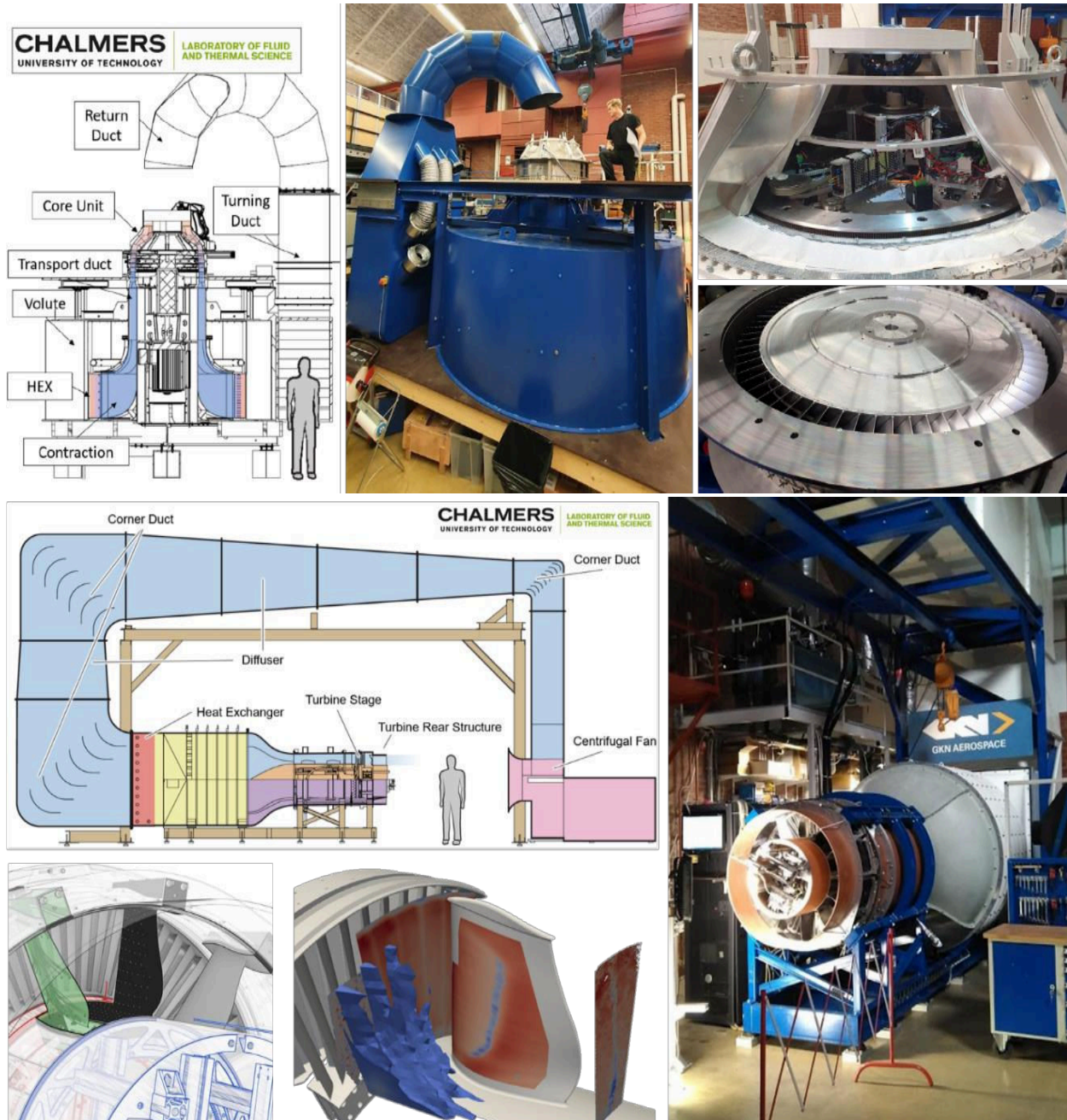


Figure 9 - Schematics of Chalmers low-speed facilities. The compressor (top) and turbine rear-structure (below) facilities are designed to achieve an accurate low-speed aerothermal representation of a state-of-the-art engine's components for future engine applications.

The compressor facility, shown in the upper part of Figure 9, is commissioned as part of ENABLEH2 to investigate and validate the performance of integrating novel cryo-heat-exchanger concepts for intercooling in the compressor duct. The facility and compressor are designed to accommodate a diversity of instrumentation and for ease of access. The compressor stages can be accessed at 28 locations, six of which have traverse capabilities of a full span 18-degree sector, to be used at the rotor-stator interfaces. The traverses can be replaced with windows for optical access when performing Particle Image Velocimetry (PIV) or flow visualisation within the compressor. At the rotor outlet-guide-vane interface, four independent traverse systems provide a 360-degree access for more detailed studies. The open pressure recovery at the exit of the intermediate compressor duct allows for full volume traverse access by a robot arm and easy access for IR thermography.

The facilities as shown in Figure 9 provide a set of flow conditions that are suitable for validating new heat-exchanger concepts at low TRL level. For instance, the engine exhaust facility provides an operational envelop that spans over a range of conditions that cover most of the existing aeroengines. Tests have been conducted at Reynolds numbers from as low as 50,000 up to design conditions at 465,000. On the other hand, the compressor exhaust facility provides a nominal chord Reynolds number of 600,000. Moreover, the key compressor design aerodynamic metrics such as stage loading, and flow coefficient are matched to the performance of a high-speed low pressure compression system designed for integration in a future geared-turbofan engine. This flow conditions, together with representative geometrical parameters such as aspect ratio, hub-to-tip radius ratio, and radial off-set ratio provide the desired environment to test the feasibility of integrating radical heat-exchanger concepts in the flow-path.

Safety and Airport Infrastructure

The introduction of hydrogen as a fuel for civil aircraft, in both gaseous and liquid forms, and the associated supporting airport infrastructures, pose a variety of challenges in relation to safety that will need to be carefully managed. Hydrogen gas has very wide flammability limits (4–74% at NTP), in comparison to conventional aviation fuel (Jet A-1), and thus will form flammable gas mixtures over a much greater range, particularly if released in a confined or enclosed space. Hydrogen has an extremely low minimum ignition energy (MIE) that is an order of magnitude less than for Jet A-1. Hence it can be ignited much more readily. Hydrogen also has a much greater propensity to detonate and can undergo a deflagration to detonation transition (DDT) under a wide range of circumstances (e.g., congestion or confinement) and at fuel-air mixture ratios producing highly damaging detonations. At typical ambient temperatures and pressures a Jet A-1 spill is unlikely to present an explosion risk as its vapour pressure is insufficient to form a flammable atmosphere above the liquid surface, whereas LH₂ spills would readily form flammable gas clouds capable of being ignited by relatively weak sparks in the vicinity.

The high density of LH₂, when compared with gaseous hydrogen, allows for significantly more efficient storage, transport and distribution, as much larger quantities can be stored at low pressure in lighter

tanks. However, LH_2 must be maintained at extremely low temperatures (20.4 K at sea level atmospheric pressure) to be kept as a cryogenic liquid. Above this temperature it will vaporise and boil vigorously releasing hydrogen gas. At ambient temperatures hydrogen gas is extremely buoyant and will rise and disperse rapidly if released in an open environment. However, at very low temperatures, of 22 K or less, hydrogen vapour has a density which is greater than that of ambient air and hence under certain circumstances it also has the potential to behave as a dense gas.

Following a LH_2 release due to an accidental leak or rupture, a range of different hazards and consequent effects can occur depending upon the nature of the release and as to whether or when an ignition source is present. In the event of an immediate ignition of the LH_2 release the hydrogen will burn as a fire, emitting thermal radiation and causing harm via burn injuries/fatalities, structural damage, and incident escalation. The type of fire behaviour exhibited will be dependent upon the nature of the release. If the LH_2 leak forms a liquid spill pool, it can vaporise to produce a flammable hydrogen-air gas mixture above the pool, which if immediately ignited will then burn as a pool fire (burning gas flame fed by a vaporising liquid pool). If the release of vaporised hydrogen gas is very rapid and of short duration (driven by buoyancy or momentum) it can burn as a fireball - a rapidly rising expanding ball of flame. If the LH_2 leak is released as an atomized liquid or gaseous jet, which is then ignited it will burn as a jet fire. If an ignition source is present at the leak location the hydrogen gas release will disperse and travel away from the spill point forming a flammable gas cloud. If it should then encounter a remote ignition source then the cloud could ignite, resulting in a flash fire causing burn injuries/fatalities or (if in a congested or confined area) a vapour cloud explosion causing harm via blast injuries/fatalities, structural damage, and incident escalation. The flame can also propagate back to the LH_2 pool producing a pool fire. Even if no ignition source is present, the cryogenic cold gas cloud released from the LH_2 could still represent a low temperature hazard that can cause harm via frostbite and lung injuries/fatalities to any people and/or structural damage to any unprotected equipment that it comes into contact with.

As part of the ENABLEH2 project, work has been carried out to study the large-scale hazards posed by LH_2 use in civil aviation and to carry out LH_2 release and dispersion modelling of large-scale releases and their potential hazard effects for airport storage and aircraft tank failure/rupture/leak scenarios. A variety of different hazard types and accident scenario case studies have been considered. The numerical simulations were performed using the FLACS CFD model which provides capabilities for carrying out safety studies by simulating accident scenarios involving fluid flow behaviour in complex 3D geometries by modelling flammable gas hazard effects such as the dispersion of flammable gas clouds, gas explosions and blast waves, and pool and jet fires

The results of the study indicate that, in the event of accidental fuel spill, LH_2 has some safety advantages over Jet A-1. Modelling of LH_2 pool fires suggests they exhibit a smaller thermal radiation hazardous distance and deliver a lower thermal dose than those found for comparable Jet A-1 pool fires. Figure 10 shows an example of the predicted radiation heat flux incident on a LH_2 aircraft.

The rapid vaporisation of instantaneous, unconstrained, LH_2 spills produces short duration fires such that the fuel spills will completely evaporate and burn-out rapidly. Hydrogen fires will also emit a lower fraction

of their heat as radiation and are clean burning such that no toxic smoke is produced (unless other materials become involved). However, the results also suggest that there will also be additional hazards associated with LH₂ leaks and spills due to the dense gas cloud dispersion behaviour that is predicted, and the extent of the flammable gas cloud that can be formed at ground level downwind of the spill and the potential for accompanying flash fire/jet fire and explosion hazards. The hazard consequences produced may be accentuated if the prevailing wind could transport the cloud under the body of the aircraft where it could be partially confined, or towards an airport terminal building, or to the side of the aircraft passenger operations are taking place.

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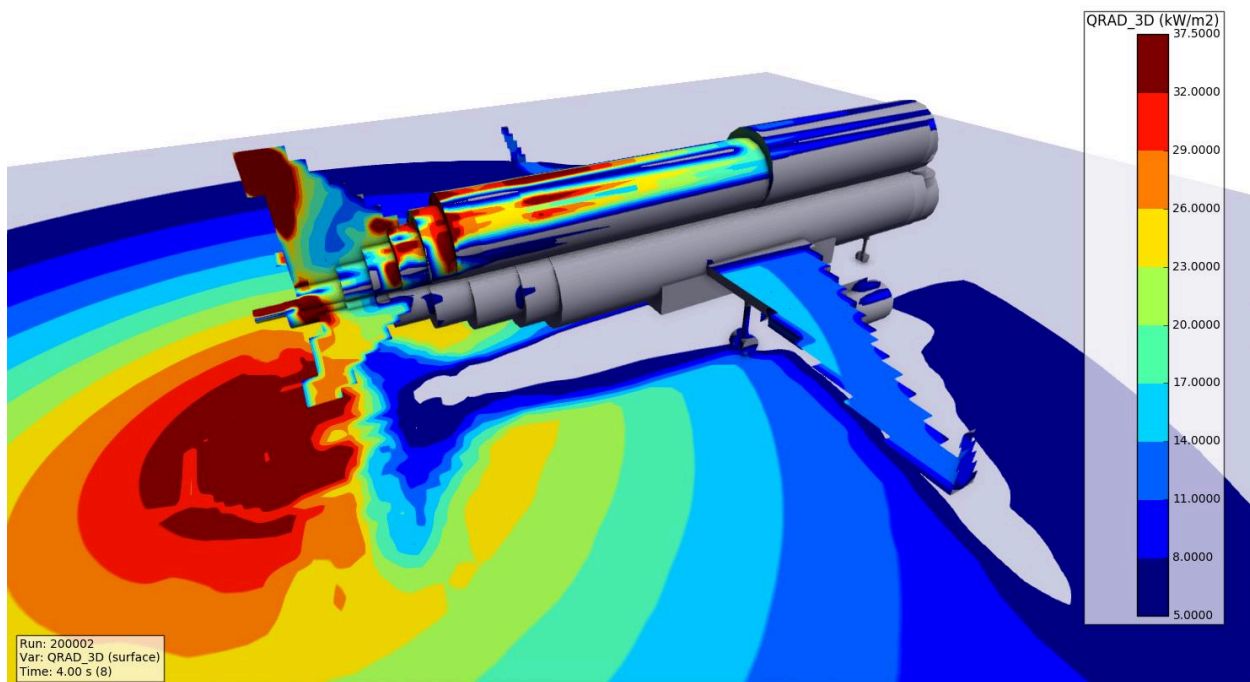


Figure 10 – The predicted radiation heat flux incident on the ground and the aircraft surfaces.

These preliminary results would seem to suggest that, at least for a relatively small LH₂ pool fire, it may be acceptable for the aircraft to be refuelled with passengers onboard, as they should be adequately protected from the effects of thermal radiation inside the aircraft. Indeed, provided the LH₂ pool fire has a very short duration the best strategy might be for the passengers to stay put inside the aircraft until the fire has burnt out. However, there are also the consequences of a delayed ignition resulting in a flammable gas cloud and the potential for a flash fire or explosion to consider. In the case of a flash fire the passengers should also be adequately protected from the effects of thermal radiation for a short duration inside the aircraft. However, in the event of an explosion the outcome is less clear-cut and would be dependent upon the overpressures generated and the aircraft's ability to withstand them.

It may well be that having passengers on board is not such an issue as they are relatively well protected, from an explosion/fireball occurring outside the aircraft. However, existing Jet A-1 fuelling arrangements where aircraft may be adjacent to terminal buildings and with other personnel such as baggage handlers in proximity, need to be re-assessed for the use of LH₂. An aircraft fuselage arguably has considerably better explosion resistance than a terminal building. That said hydrogen releases to the open air tend not to generate strong blast waves unless there are mechanisms to generate turbulence (e.g., obstacles or high velocity release) or a detonation wave propagates into the hydrogen/air cloud from a duct or channel. A worst-case scenario, although unlikely, could be a large spill dispersing and finding an ignition source inside a duct or channel within an aircraft or other machinery, resulting in a DDT which then propagates back into the unconfined cloud. These scenarios will also need to be explored.

With all the challenges that hydrogen fuelled aircraft present, it should be noted that all fuels carry an inherent risk of potential hazards which must be mitigated prior to adoption in commercial service, such that serious fires are an extremely rare event in aviation. Specific hazards that relate to hydrogen must and will be addressed during research and design, ENABLEH2 will also contribute to these efforts.

Hydrogen Aircraft Technology Evaluation

Transitioning to hydrogen-fuelled aircraft poses significant technical and integration challenges. These range from design of suitable aircraft and integration of specialised systems onboard to facilitate storage of cryogenic fuels, to modifications at airport and Air Transportation System (ATS) level to cater for future operational requirements.

The technology evaluation activities within ENABLEH2 consider a number of these challenges, but are primarily focussed on identifying, modelling, and evaluating suitable aircraft concepts that can efficiently use hydrogen as a fuel, while synergistically exploiting its unique properties. The overall objective is to quantify, for defined missions, the environmental emissions reduction potential and cost benefits of the LH₂ fuelled aircraft concepts. These will be compared with best-case scenario projections for reference aircraft utilising Jet A-1, drop-in biofuels, and LNG, under various fuel price and emission taxation scenarios.

Technology down-selection

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The technology evaluation process began with identifying top-level aircraft requirements consistent with the requirements of comparable reference aircraft, a common standard for modelling the technology, and plausible scenarios to provide a consistent basis for the propulsion system and aircraft-level impact analysis. This included specification of aircraft and engine technology levels, detailed mission definitions and plausible long-term fuel cost and emission taxation scenarios. To assess suitable market conditions under which hydrogen aircraft would be viable assets, three policy scenarios are considered. These include economic assumptions signifying: business as usual, progressive environmental awareness and heightened environmental awareness. To provide a wider base for assessing the business risk, additional supplemental scenarios were also identified which included considerations of future costs of electricity, fossil fuels and environmental taxation.

Future aircraft concepts fuelled with hydrogen will be fundamentally different in terms of overall design and hence a technology down-selection process was adopted to identify the better options amongst the many possible. This therefore involved identifying suitable LH₂ aircraft concepts for short-to-medium range (SMR) and long range (LR) applications. In total, 31 potential airframe architectures and 21 propulsion-system arrangements were analysed in a two-step process. Those aircraft assumed to have tightly coupled aero-propulsive systems, designed to accrue the synergistic benefits of using cryogenic fuel, were designated as max synergy aircraft concepts. Aircraft concepts were selected based on a comprehensive set of key criteria for each application, which related to operating cost, revenue, noise, and safety. The two max synergy concepts finally selected were based on a Tube and Wing (T&W) design for SMR missions and a Blended Wing Body (BWB) design for LR missions. Two LH₂-fuelled low risk aircraft concepts (Figure 11 and Figure 12), based on minimal modifications to conventional LR and SMR reference aircraft, were also selected for assessment. They represent designs that could be derivatives of conventional airliners and delivered with reduced risk technology investment and time to market, while meeting all stipulated performance and safety criteria.

Modelling and assessments

To quantify the potential of the LH₂ aircraft concepts, suitable reference aircraft were modelled for comparison. These were based on conventional Tube and Wing (T&W) aircraft, such as the Airbus A321 NEO for SMR missions, and the Airbus A350 or Boeing 777-9X for LR missions.



Figure 11- LH₂ SMR lower risk aircraft concept

The baseline technologies were assumed to be representative of aircraft with an entry into service (EIS) in the year 2020 and fuelled by Jet A-1. With these as baseline, the reference aircraft concepts were further developed and modelled assuming technology improvement factors representative of Y2050 EIS, whilst ensuring they matched the pre-set top-level aircraft requirements. The 2050 concept aircraft were assumed to be able to utilise Jet A-1, drop-in biofuel, or LNG as fuels. Additionally, as part of the assumed set of technologies in the Y2050, an LNG-fuelled blended wing body aircraft concept for LR missions was also sized and modelled. To simulate representative performance of aircraft operating on biofuels and LNG, suitable modifications were made to fuel properties and airframe design where necessary. Additionally, for the cases wherein LNG was assumed as the fuel, the size, weight and drag of integrated cryogenic tanks was calculated and included into the performance analysis. Utilising these analytical models, flight missions were simulated to undertake detailed performance and emission assessments, lifecycle CO₂ calculations and preliminary cost estimations.



Figure 12- LH₂ lower risk aircraft concept

The modelling of LH₂ fuelled aircraft included the two “max synergy” concepts derived through the down-selection process, and additionally, the two low risk concepts based on modification of conventional LR and SMR aircraft. The “max synergy” aircraft concept for SMR application, designated as Safran’s *Cobalt Blue*, was assumed to have a circular fuselage cross-sectional area with a mid-wing (Figure 13). The internal LH₂ tanks are assumed to be installed in the wing roots and between cabin and cargo decks. The aircraft has a series partial hybrid electric propulsion system which includes an LH₂ fuelled tail mounted (or buried) single gas turbine and wing mounted ducted boundary layer ingesting (BLI) electric fans powered by fuel cells.



Figure 13-SMR-max synergy concept *Cobalt Blue*.

The LR “max synergy” aircraft concept is based on a blended wing body design (Figure 14). Based on the NASA’s N3-X design, the fuselage is extended in length to accommodate 414 passengers. The propulsion system is assumed to have a partial turbo-electric distributed configuration and includes two turbofan or

turboshaft engines buried at the wing root to provide electrical power generation and part of the thrust. The electric power drives an array of fourteen BLI fans above the fuselage.



Figure 14- rendition of LR- max synergy concept BWB aircraft.

The LR “max synergy” aircraft concept is based on NASA’s N3-X BWB design but scaled-up to accommodate 414 passengers and to provide more internal volume for the LH₂ tanks (Figure 14). A superconducting turboelectric distributed propulsion system takes power from turbofan or turboshaft engines, buried in the wing roots, to drive an array of BLI ducted fans. The propulsion, fuel and electrical system architectures are integrated to maximise synergies, including using LH₂ for cryo-cooling the superconducting motors and generators.

Technology and scenario evaluation studies

To establish ‘best-case’ scenarios for Y2050 technologies, preliminary assessments have been made of the reference technologies using carbon-based fuels. The assessments indicate significantly improved overall efficiency relative to representative state-of-the-art aircraft currently in service. For both SMR and LR aircraft concepts fuelled with Jet A-1, results indicate up to 24% lower mission fuel burn and CO₂ emissions per available seat kilometre (ASK). Drop-in replacement biofuels only enable reduction of mission-level CO₂ emissions by a few percent but have the potential for very significant reductions in emissions over the full lifecycle of the fuel.

Utilisation of LNG is found to offer modest reductions in mission-level and lifecycle CO₂ reductions relative to Jet A-1, which is attributed to the penalty incurred because of the requirement of large cryogenic tanks. However, in comparison, the LNG-fuelled BWB aircraft was able to achieve significant reductions in emissions due to higher lift/drag ratio, a more efficient boundary layer ingesting propulsion system and ability to achieve better fuel tank integration due to the larger internal volume available in the airframe.

The modelled LH₂ concept aircraft are currently being assessed against the Year 2050 reference aircraft. As part of the technology evaluation assessments, an investigation of trade-offs between block fuel-burn/energy efficiency, extent of contrails formed, mission level NO_x emissions and operating costs will be undertaken. This will be assessed for a set of fuel prices and emission taxation scenarios. For various

LH₂ production routes, the study will also include lifecycle 'well-to-wake' CO₂ emission and cost assessments based upon various fuel price and emission taxation scenarios.

Summary

With the increasing attention that LH₂ and its environmental benefits is receiving globally, ENABLEH2 is well placed to accelerate the entry into service of LH₂ aircraft. ENABLEH2 will achieve this by maturing the following key enabling technologies through a combination of numerical and experimental research and innovation.

- Ultra-low-NO_x hydrogen micromix combustion systems.
- Exploring the formidable heat sink potential of hydrogen to enable advanced propulsion technologies including compressor integrated cooling and variable cooling.
- LH₂ fuel tank and fuel system models.

A comprehensive suite of numerical models has been developed to quantify the performance and emission benefits of LH₂ fuelled aircraft.

ENABLEH2 is also addressing the challenges associated with the introduction of hydrogen for aviation and will deliver:

- A comprehensive safety audit, characterizing and mitigating hazards to support integration and acceptance of LH₂ at aircraft, airport, and operational level.
- Life cycle costs and CO₂ emissions relative to best case scenario projections for Jet A-1, biofuels, and LNG for different fuel price and emissions taxation scenarios.

ENABLEH2 is providing detailed roadmaps for each of the 12 technology research strands below that have been identified by ENABLEH2 partners and key civil aviation stakeholders who form part of the ENABLEH2 IAB. These research strands are as follows:

Hydrogen on the 'ground':

- Decarbonising power generation.
- Hydrogen production, liquefaction, and distribution apparatus.
- Airport infrastructure and aircraft fuelling systems for LH₂.

Hydrogen in the 'aircraft':

- Ensuring safety with hydrogen-fuelled aviation.
- Design of aircraft fuel systems for LH₂.
- Propulsion systems using hydrogen as fuel (including distributed propulsion options).
- Combustor design and emissions reduction with hydrogen.
- New commercial aircraft designs for LH₂.
- Aircraft operation and maintenance with LH₂ fuel.

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Adapted from Luis(Nando) Ochoa,

And finally, hydrogen economics, sustainability, and feasibility:

- Aircraft economics with LH₂ vs. alternative fuels.
- Environmental impact research, and assessment of hydrogen vs. alternative fuels.
- Integration of research funding and timeframes for the introduction of LH₂ fuelled aircraft.

By the conclusion of ENABLEH2 detailed roadmaps for each of these research strands will be published.

For Further Reading

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