AEROSPACE TECHNOLOGY INSTITUTE

Hydrogen Capability Network

Cryogenic Hydrogen Thermofluids Research Workshop Summary

August 2024

Contents

The ATI creates the technology strategy for the UK aerospace sector and funds world-class research and development. Hydrogen Capability Network acts on key recommendations from FlyZero to become an essential enabler of UK technology development.

Executive Summary

The move to liquid hydrogen as a fuel source, as recommended by the Aerospace Technology Institute's (ATI) FlyZero project, will be the biggest disruptor to the aerospace technology landscape since the introduction of the gas turbine. To meet the ambitious entry into service dates set by airframers, the transition to liquid hydrogen will require significant and rapid development of new technologies. A hydrogen fuel storage and delivery system will require a greater depth of knowledge of the behaviour and impacts of cryogenic hydrogen than is currently present within industry or academia within the UK.

The ATI's Hydrogen Capability Network (HCN) has identified a priority need to bolster fundamental and pre-normative research in the UK to support liquid hydrogen fuel systems technology development with a primary focus on:

- Cryogenic hydrogen thermofluids behaviour
- Fundamental material behaviour at cryogenic temperatures and hydrogen environments
- Cryogenic hydrogen health and safety protocols, modelling, and testing

The HCN are now working to develop collaborative strategic research projects on these topics, considering the international landscape and industrial priorities.

This report details the outcomes from a workshop on hydrogen thermofluids challenges and potential solutions. The workshop had 20 attendees from 17 organisations, including industry, research organisations, and academia.Appendix 1: Workshop Attendees

The workshop concluded that greater knowledge of the fundamental science behind cryogenic hydrogen thermofluids behaviour is required in both experimental and modelling disciplines. Consideration should be given to multi-physics, multi-scale, and multi-fidelity modelling techniques & experiments, with key research areas including heat transfer, mass transfer, and fluid dynamics. Scenarios of particular interest are storage, pipe flow, pressurisation, heat exchange and loss of containment. These reflect the opinions of those who attended the workshop and are not intended to be viewed as developed proposals for action, nor exhaustive.

Over the next 6 months the HCN will build on these requirements to determine the best route to addressing the research challenges that exist for the aerospace sector to be successful in technology development. Developing a challenge-based approach and as appropriate collaborative strategic research projects to enable industrial R&D.

Introduction

The FlyZero project developed roadmaps covering the technologies needed for liquid hydrogen (LH2) flight to be viable[1]. These cover topics that are both generic (such as automation and digital twins) and specific (such as aerodynamic modifications to manage dry wings, fuel cell development and gas turbine hydrogen combustion), as illustrated in Figure 1Figure 1. In work carried out by the Hydrogen Capability Network (HCN), involving engagement with key stakeholders, it has been demonstrated that the UK has strong existing knowledge and research capability in many of the topics required to deliver an aircraft capable of liquid hydrogen powered flight. There is, however, a clear exception with on-aircraft cryogenic hydrogen fuel storage and delivery systems. Thus, intervening to accelerate the development of fundamental knowledge and capability in this area within the UK will enhance the UK's ability to contribute to the development of zero carbon aircraft. This aligns directly with both Government's Net-Zero policy objectives and the objectives of the HCN.

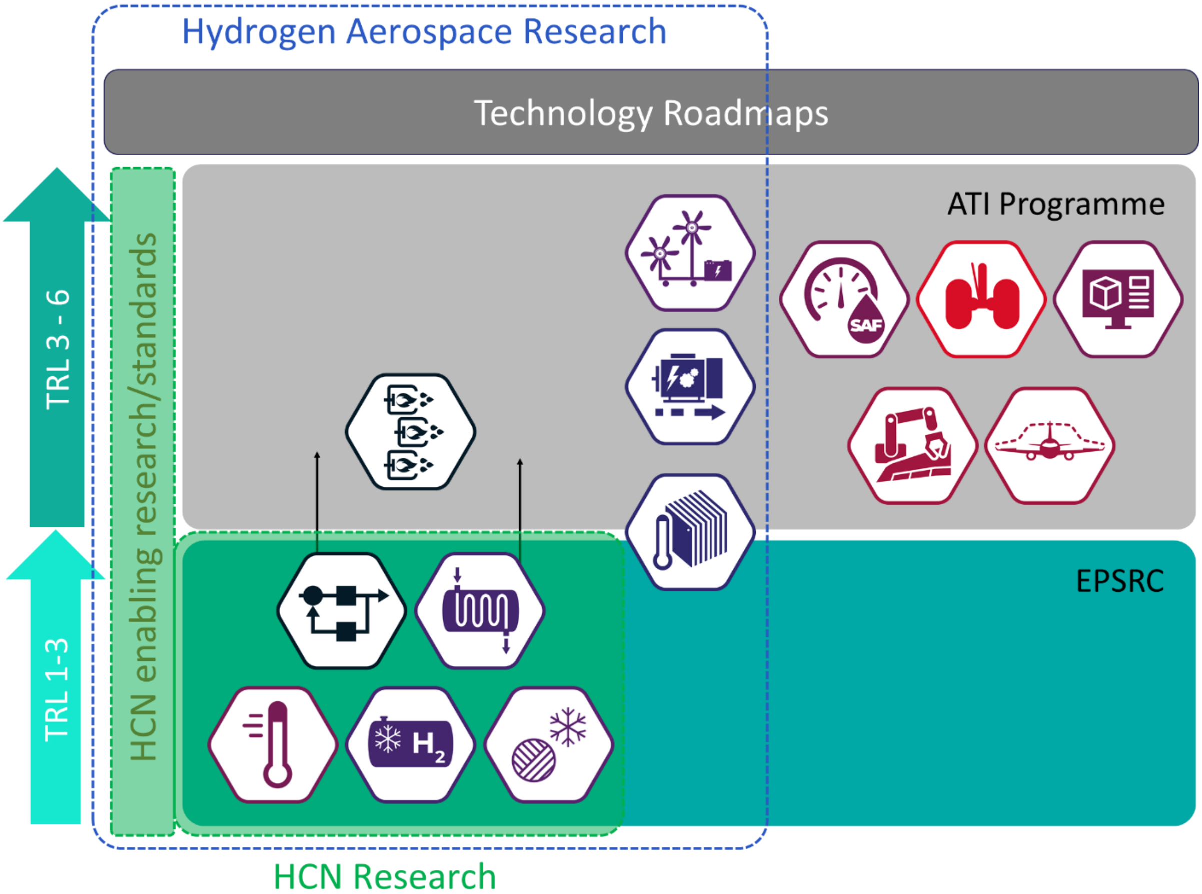

Figure 1 Technologies in which development is required to deliver LH2 powered flight

The challenge relates specifically to the storage and movement of hydrogen fuel between the fuel tanks and power source across a large range of fluid temperatures and pressures. Key research areas include the management of fluid phase transition from liquid to gaseous states in a controlled manner to ensure component function and life; the impact of hydrogen on the component integrity; and how to sense and manage hydrogen leaks safely, particularly in flight. While the requirements have initially been driven by aerospace, there is relevance to other sectors that have plans for the use of liquid

[1] FlyZero Reports Archive - Aerospace Technology Institute (ati.org.uk)

hydrogen in the future, and a link to these requirements is being maintained through the Hydrogen Innovation Initiative (HII)[2].

During the first 12 months of the HCN, the following topics were identified as requiring particular focus:

- Cryogenic hydrogen thermofluids behaviour
- Multiphysics understanding of materials at cryogenic temperatures
- Cryogenic hydrogen health and safety protocols, modelling, and testing

Now the HCN is further developing these topics into research proposals, and this report captures the feedback and outcomes from a workshop focussed on cryogenic hydrogen thermofluids behaviour held on 17th April 2024 to capture the challenges and potential solutions for hydrogen thermofluids. The workshop was attended by 20 people from 17 organisations, including industry, research organisations, and universities, as listed in Appendix 1.

[2] Home - Hydrogen Innovation Initiative

Summary of challenges

Approach: the workshop participants were first placed in breakout groups with a mix of academic and industrial backgrounds and asked to develop a list of the key challenges and issues in the field of thermofluids that need to be overcome to realise LH2 flight. The discussions from all the breakout groups were then collated and grouped into a list of key topics that were then agreed amongst all participants.

The key topics that were identified, and the broader discussions that took place in the workshop under these topics, are summarised in the text below and the following sections:

- Phenomena
- Experimental testing - for validation of modelling techniques
- Engineering challenges - associated with the application of liquid hydrogen
- Modelling methods and tools

Phenomena

There is a need to understand the fluid dynamics of cryogenic hydrogen through its phase transitions and changes in ratio of spin isomers. The fundamental understanding of heat and mass transfer on multiphase flows needs to be understood to develop robust and experimentally validated modelling tools. This will enable the optimisation of thermodynamic cycles in the distribution and conditioning of fuel from the storage tank to its utilisation.

There is a need to define further heat transfer coefficients, Prandtl number, specific heat capacity, and critical heat flux, especially in the range close to the critical point, for different flow conditions and multi-phase flows.

These definitions must be combined with an understanding of surface-fluid interactions and flow properties, such as pipe friction factor, boundary layer topology, wall wetness, gas nucleation, and Reynolds numbers. These items all require further investigation in relevant conditions, including vibration and in multi-phase flow conditions.

Deeper understanding of hydrogen compressibility, viscosity, and cavitation behaviour are required across phases, particularly for pump design. In electromechanical systems, consideration must be given to electrical and magnetic effects of and on hydrogen in order to control static electrical hazards and understand the impact of LH2 on instrumentation.

Significantly, there is a lack of knowledge of many fluid properties close to the critical point, causing a significant challenge in modelling this condition. There are potential thermofluids singularities/ universality near the critical point and this leads to a requirement for exploring other approaches such as statistical analysis and the potential for equation of state modelling refinement around critical point.

There is a need for greater understanding of the transition and effects of the composition of hydrogen, covering the fluid phase, ratio of spin isomers of hydrogen, and any potential contaminants.

The complete list of topics discussed and considered by the workshop is summarised as:

- Heat transfer
- Mass transfer
- Fluid dynamics/ multi-physics flow
- Solidification/ slush hydrogen

- Ortho/ para
- Saturation and critical point
- Liquefaction

Experimental testing

Comprehensive experiments are required to validate fundamental fluid properties and numerical models. More facilities and capability are required to undertake these experiments and will need to be co-ordinated in order to avoid duplication in the UK. The supply of liquid hydrogen at appropriate quantities / cost for these facilities is also highlighted as an on-going challenge.

Collaboration across the development and operation of new facilities is required, including sharing best practice learnings. Sharing of knowledge is particularly important in the design of safety systems, and there is some interest in the development of proxy fluids to liquid hydrogen to mitigate the H&S requirements for some experimental testing. The development of new open access fundamental data sets that can be used in model benchmarking and design highlighted the need to share as much of the generated results as possible.

The variety of measurement types and scales across the experimental testing requirements leads to a need for a diverse range of test apparatuses that could be co-located or spread throughout a broader network. Specific challenges were highlighted in sourcing the instrumentation required to facilitate these experiments. There is a lack awareness of appropriate flow sensing technologies which have been validated to operate for two phase cryogenic fluids, with a concern that some sensors are intrusive. Also potentially lacking are inline sensors that detect fluid phase mixtures, spin isomer ratios, and metering and control instrumentation that operate at cryogenic temperatures to the requirements of these experiments. A mapping exercise is needed to determine currently available sensors.

The complete list of topics discussed and considered by the workshop is summarised as:

- Experimental testing
- Validation and verification
- Fundamental properties generation
- Facilities
- Liquid hydrogen supply
- Design of experiments
- Proxy fluids
- Montoring, sensing, and control

Engineering challenges

Beyond the fundamental understanding of the behaviour and properties of liquid hydrogen, there are engineering challenges facing the application of liquid hydrogen as a fuel that require research.

The application of liquid hydrogen in specific scenarios also requires further understanding through modelling and experimentation. Some scenarios highlighted by industry are below, with consideration needed to be given to the impact of altitude and turbulence that may be unique to aircraft:

- Tank design
    - Stratification and sloshing with concerns over temperature distribution
    - Boil-off and condensation during different flight phases, including dormancy
- Pumping

    - Multi-phase composition in pumping
- Upset conditions
    - Failure event safety modelling
- Heat exchangers and pipes
    - Flow characteristics, heat exchange, phase transition, ortho and para-hydrogen conversion

Challenges were highlighted around the design of systems to handle liquid hydrogen, with a lack of good practice guides and existing expertise noted. Design of hardware and control systems for pressure relief, venting, boil-off management, and hydrogen leakage detection were raised as critical safety concerns. Consideration needs to be given to effective purging of valves and systems to prevent contamination or ice build-up. Other concerns were raised in the design of systems to ensure access for inspection and maintenance as well as maintaining the effectiveness of insulation. The lack skills or experience in the design of these systems was discussed, with challenges arising from elevated perceptions of risk and lack of best practice.

As found in previous activities, there are significant knowledge gaps in the behaviour of materials in cryogenic hydrogen environments, including mechanical, thermal, and transport properties. The HCN team are working to address materials fundamental understanding in a separate intervention, as mentioned in the introduction along with a focussed proposal to develop materials testing standards[3]. Related understanding of fluid-surface interactions and tribology of materials and components has been highlighted as another gap in understanding, particularly in relation to multi-phase flow. The potential for material surfaces to catalyse spin isomer transition or other shift other equilibriums could have a direct impact on thermofluids behaviour.

The particular engineering challenges discussed in the workshop are summarised below:

- Engineering challenges
- Surface and material interaction
- Tribology
- Scenarios
- Pressurisation
- Sealing, insulation, and leakage
- Contamination
- Systems engineering
- Fluid mixtures
- Skills

Modelling

A combination of modelling techniques is required to address knowledge gaps, including multi-physics and multi-scale models that allow the coupling of atomistic to continuum scales. Both high fidelity models for precise understanding of phase stability and low fidelity models for flow and thermal analysis to aid iterative design will be required. Concerns were raised about current models that are based off limited historical data which does not allow for quantification of uncertainty, and often result in discrepancies between models.

[3] Hydrogen Capability Network (ati.org.uk)

Model benchmarking, with dimensionless and generic geometries, would provide a route to tool validation and benchmarking across methods. Specifically, there is a need to accelerate the development of confidence in numerical methods (CFD) in order to move towards best practice. Equations of states for a variety of properties, including phase, would be useful for industry.

A summary of the modelling challenges considered by the workshop is as follows:

- Techniques
- Uncertainty
- Benchmarking
- Confidence
- Toolsets
- Data driven models

Challenge prioritisation

Approach: the workshop participants were asked to vote on the challenges highlighted to provide a technical prioritisation. Each participant received ten dots to indicate their highest priority challenges. The sums of these votes are shown in Figure 2, also indicating the different views or priorities of industry to research organisations.

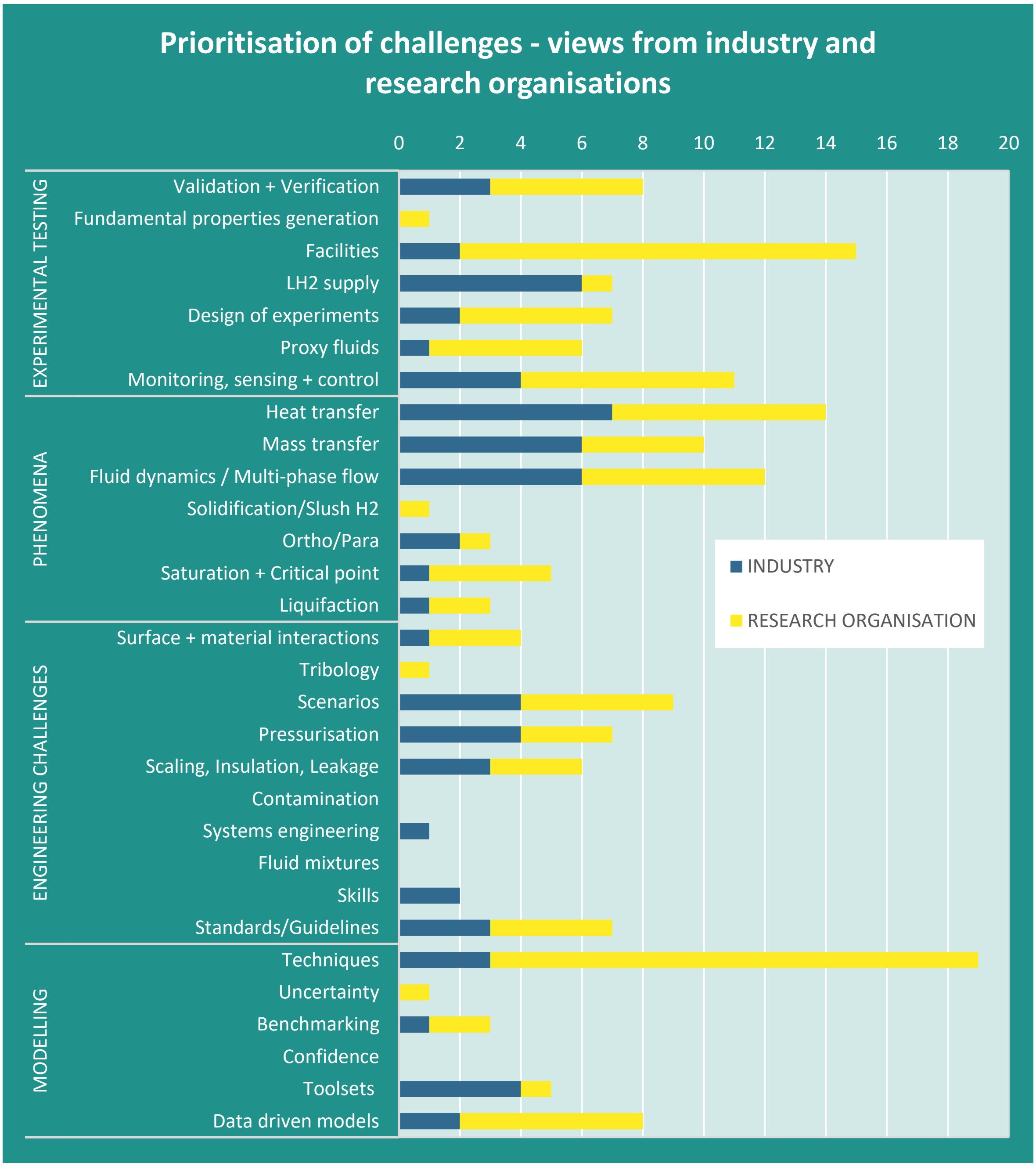

Figure 2: Prioritisation of Challenges

It can be seen that industry expressed most interest in research to develop our understanding of phenomena including heat transfer, mass transfer, and fluid dynamics. Industry also highlighted the supply of LH2 for experimentation as a key area. Research organisations expressed priority should be given to developing modelling techniques and experimental facilities. The value of monitoring, sensing, and control equipment for experimentation, and the benefit of directing research to scenariobased analyses has agreement across both industry and research communities. Hence, further work is needed to resolve the different industry and academic perspectives to identify which topics best support building the capability in the academic community, while also underpinning technology development.

Addressing these challenges

Approach: the workshop participants were asked to provide their view as to how these challenges may be addressed through research and comments raised in the workshop are described in the below table. These reflect the opinions of those who attended the workshop and are not intended to be viewed as developed proposals for action, nor exhaustive.

Challenge area	Proposed activity
Phenomena	• Maintained property model library, including raw data and fitting parameters • Individual and multi-physics design of experiments - support and co-ordination • Research to understand practical impact of ortho / para hydrogen • Canonical studies between phase and multi-phase conditions, heat transfer, and surface properties • Property evaluation near critical point • Dimensionless groups to understand compressibility • Analysis of methods to minimise the boiling curve, and boiling and sub-cooling control

Experimental testing	• Development of experimental capability to test:
	  ○ Near critical point
	  ○ Fluid-structure interaction, with vibration variation
	  ○ At altitude conditions
	  ○ With aerosol / droplet liquid hydrogen
	• Instrumentation development, including for ortho / para detection and fluid mixtures
	• Proxy fluid development, to allow for safer and lower cost operation
	• Data sharing framework, with open-source data interpolation
	• Integration of experimental and modelling capability, including empirically derived models
	• Best practice for safe facility design and experimental testing
	• Case study repository
	• Support for small-scale LH2 supply
	• Test geometry definition

Challenge area	Proposed activity
Modelling	• Define fidelity requirements for different phenomena for LH2 applications • System architecture design and optimisation • Development of new non-dimensional groups • Reduced order modelling for iterative component design and system level design • Equations of state • Empirical data update to support uncertainty analysis • Standards and best practise for use of modelling tools, including applicability of CFD • Conference cross-skilling • Training for digital twins • User defined function integration into commercial package • Centre for doctoral training (CDT) for CFD for industry • Application of physics-informed neural network, machine learning, and high-power computing • Application of quantum computing
Engineering challenges	• Design envelop definition from industry • Generation of design charts for compressible liquids • Investigation and benchmarking of instrumentation uncertainties • Science focussed scenarios, including definition of normal and upset conditions • Cross industry course • Creation of empirical model for validation of fluid mixtures • Tribology analysis, including analysis of lubricants and low temperature and vacuum • Surface analysis using a soaking rig • Test rig design

Next Steps

This workshop has captured the current challenges related to thermofluids for liquid hydrogen powered flight as viewed by the workshop attendees. Work will continue to map out the UK's capabilities in these areas and comparing this to international capabilities. This work will identify gaps and opportunities for the UK, which, together with industry driven priorities, will identify where investment will give the maximum benefit to the UK. It is anticipated that this work will complete by April 2025, when a document laying out the recommended strategy for boosting UK capability in the field of liquid hydrogen fundamental and pre normative research.

To contribute to the UK mapping activity, please use the form in the following link: https://forms.office.com/e/HUf6cCSqb6

Appendix 1: Workshop Attendees

Organisation
Advanced Manufacturing Research Centre (AMRC)
Airbus
Eaton
GKN Aerospace
Parker Meggitt
Rolls-Royce
Unitrove
Birmingham
Cranfield University
Det Norske Veritas (DNV)
University of Bath / IAAPS
University of Nottingham
University of Oxford
University of Strathclyde
UK Atomic Energy Authority (UKAEA)
Department for Business and Trade (DBT)