Hydrogen Capability Network

Cryogenic Hydrogen Thermofluids

Global Research Landscape

May 2025

About

This report is authored by the University of Nottingham, in response to the Hydrogen Capability Network's Global Capability Research Tender for the topic of **Fundamental Research into Cryogenic Hydrogen Thermofluids Behaviour.**

Lead Author

Carol Eastwick (University of Nottingham)

Supporting Team

Ajith Ambalakatte, Evgenia Korsukova, Sandeep Mouvanal, Sarah Walker and Sarah Fletcher (University of Nottingham).

Huw Edwards and Rebecca Shaw (Hydrogen Capability Network).

About the Aerospace Technology Institute

The **Aerospace Technology Institute (ATI)** is an independent organisation that works alongside government and industry to transform UK aerospace through technology and innovation. The ATI is funded equally by the **Department for Business and Trade (DBT)** and by industrial recipients of project grants who pay a small levy. ATI projects are chosen and overseen through close collaboration with Innovate UK and DBT.

As well as running this portfolio of R&T projects, the ATI conducts strategic research projects to help define and answer systemic questions of value to the UK aerospace sector. In 2022 the ATI published the findings of the **FlyZero** project, which concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft.

The ATI Programme has made several investments in liquid hydrogen technologies to support the next generation of zero-carbon aircraft. The **Hydrogen Capability Network (HCN)** was launched in April 2023 funded by the Department for Business and Trade, to progress key recommendations from FlyZero which will enable the aerospace sector to deliver liquid hydrogen research and development (R&D).

About the University of Nottingham

The University of Nottingham is a Russell group university with an established engineering faculty. The university has a long history of aerospace research and development, and it is ranked in the top ten UK universities for engineering research excellence. The faculty of engineering is the first in the UK to be awarded an Athena Swan Gold Award for advancing gender equality.

Carol Eastwick is a professor of mechanical engineering and the head of the Mechanical and Aerospace Systems Research Group. Her research is focused on thermofluids and thermal management, particularly involving multiphase flow. The research team behind this report has further expertise in heat transfer, thermofluids and health and safety.

Disclaimer and Funding Acknowledgement

This work was carried out by the **University of Nottingham**, funded by the **Aerospace Technology Institute's Hydrogen Capability Network (HCN)**.

The report is based on reviews of published information available before February 2025. Although every effort has been made to ensure it reflects a comprehensive review there will be research that was not available in the public domain, unable to be translated to English or not published due to commercial or security restrictions. The ATI does not accept liability for any errors, omissions or misleading statements and no warranty is given or responsibility accepted for any actions users may take based on the content of the report. The ATI reserves the right at any time to make changes to the material, or discontinue the report, without notice.

Liquid Hydrogen Thermofluids Summary

The Aerospace Technology Institute's (ATI) FlyZero project concluded that liquid hydrogen (LH2) is the most viable zero-carbon emission fuel for future commercial aircraft. The FlyZero reports highlighted technologies which would be required to enable such aircraft to become a reality and the gaps in liquid hydrogen capability. The technological change to a liquid hydrogen architecture is revolutionary and the cryogenic hydrogen storage and fuel system faces the greatest disruption. To get to a certifiable, commercially viable system design it requires a breadth of knowledge relating to cryogenic hydrogen that does not currently exist within the sector. As such, the Hydrogen Capability Network (HCN) has identified three key areas which need to be supported:

- Fundamental research into material behaviour in cryogenic hydrogen environments.
- Fundamental research into cryogenic hydrogen thermofluids behaviour.
- Fundamental research into cryogenic hydrogen health and safety.

Workshops on these three topics were held, to identify subtopics that were of particular interest to both industry and academia. The HCN commissioned global landscaping projects to investigate the current state-of-the-art fundamental research on these subtopics in each of the three key areas, and a report has been written by academic experts on each of them. Each report highlights the global research status and gaps in which research and development is needed to enable the liquid hydrogen aircraft of the future.

The key areas identified within the thermofluids workshop were used to identify the areas of investigation within this report. This document reviews ongoing and seminal works in twelve different areas of fundamental thermofluids research across the globe to develop maps of gaps and opportunities. Fundamental research is defined as being at a TRL of between 1 and 3; it can be experimental, analytical, computational, or a combination of these. To understand the impact the fundamental research gaps have on research and development of aviation fuel systems five scenarios have been investigated, with the implications of the research gaps highlighted.

Publications have been analysed from 1950 to February 2025. The majority of the publications reviewed are from the last 15 years. Figure 1 shows the publication count from 1951 to 2025 by decade for liquid hydrogen fluid properties publication in the engineering field. Whilst this does not cover the whole Thermofluids research area it provides a good guide to the trends in publications in liquid hydrogen low TRL Thermofluids which quadrupled between the decade from 2001 to the decade from 2011.

Figure 2 provides a breakdown by country from 2000 by half decade and the prominence of China, USA and Japan are clear from this breakdown.

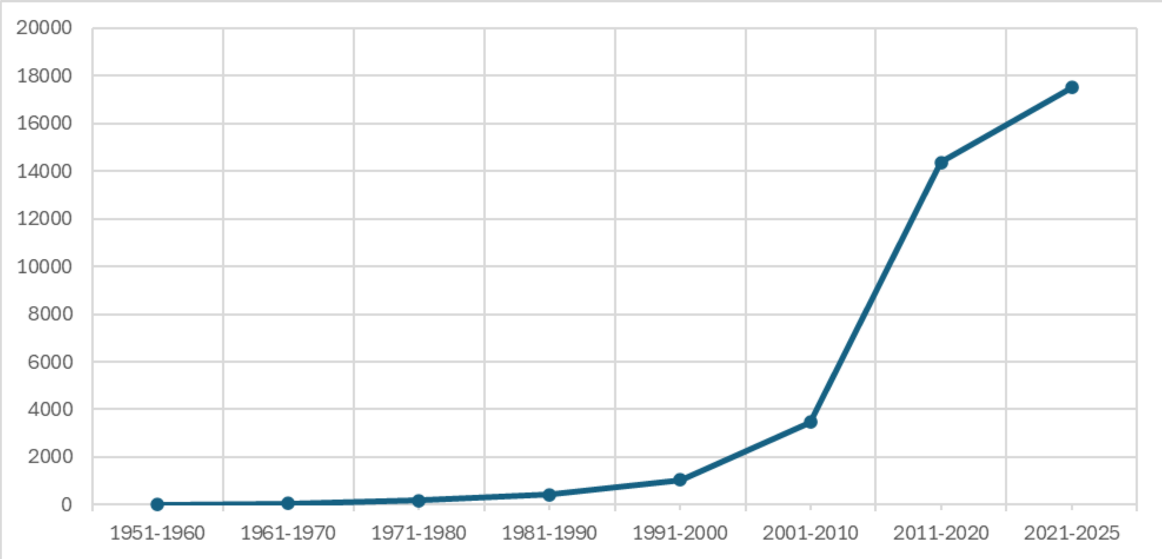

FIGURE 1: LOW TRL RESEARCH PUBLICATION COUNTS IN ENGINEERING LIQUID HYDROGEN FLUID PROPERTIES BY DECADE

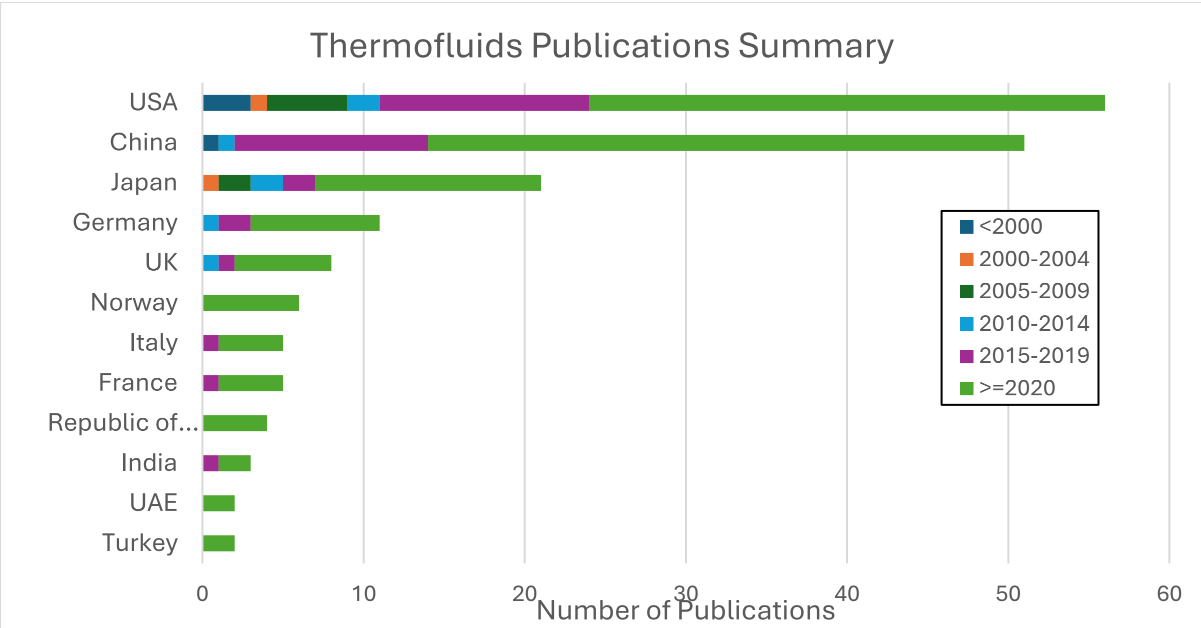

FIGURE 2: LOW TRL RESEARCH PUBLICATION IN ENGINEERING LIQUID HYDROGEN THERMOFLUIDS SINCE 2000 SPLIT BY COUNTRY, PUBLICATIONS BY HALF DECADE, HIGHLIGHTING THE DOMINANCE OF CHINA SINCE 2015.

Comprehensive understanding of liquid hydrogen (LH2) systems requires accurate data and models. These systems will be vital for the current and future green economy, from the creation and liquefaction of hydrogen to its use in energy and transport applications, including aviation.

A comprehensive understanding of LH2, both from experimental and modelling perspectives, is vital for hydrogen powered aircraft. In order for cryogenic hydrogen storage and fuel system on aircraft to be airworthy, they need to be optimised for weight and efficiency, but they also need to be certified. The path to certification requires proof of a clear understanding of the system as it is meant to operate and also in unexpected conditions. All of this work needs to build upon the fundamental data and understanding of LH2. Through this review forty-three fundamental research gaps were identified for Thermofluids of liquid hydrogen. An additional eighteen research and development gaps were identified across five practical scenarios; these being refuelling, stratification, pumping, chill down, sloshing and boil-off.

Across the different topics investigated, some global regions of expertise have been identified. The USA has multiple research institutes or areas of excellence with experimental and modelling expertise. Many of these are built around NASA sites; most of the experimental data identified in this document has links to NASA in the 1950s through 1970s. Washington State University (USA) has a significant body of research investigating the fundamentals of liquid hydrogen behaviour. The Japanese Aerospace Exploration Agency (JAXA) has LH2 experimental capabilities which are linked with various Japanese universities. Australia is developing infrastructure with a significant concentration in Melbourne. In Europe, Germany has linkages between LH2 thermofluids and materials research. In addition, the clean hydrogen joint undertaking from the European Commission, in conjunction with UKRI, supported project ELVYHS, with the European Commission fuel cells and hydrogen joint undertaking supporting PRESHLY. These projects developed linkages across Europe, including the UK, creating a community of fundamental research for liquid hydrogen. This historical research focused on generating information for specific applications, this has left gaps in fundamental LH2 thermofluids knowledge required in order for LH2 to be utilised for aviation.

Modelling work frequently goes alongside experimental work at facilities in the USA and Japan, although most models rely upon historical datasets. Multiple but sometimes incremental LH2 thermofluids modelling papers are being published in China; a minority of papers link with ongoing experimental research. Modelling software primarily links with the USA, although there are some that are developed in Europe and Australia.

From this review sixty-one key research gaps have been identified as being critical to allow LH2 systems to be developed. These research gaps can be sectioned into those which will enable further research to be undertaken, and those which are vital to enable the research to move towards higher TRLs. Here a summary of the gaps is provided under these headings. The full listing of research gaps can be found both within the body of the report and the conclusions.

Enabling Research Gaps

- Standardisation of experimental methodologies is needed to allow data to be compared against each other.
    - Fundamental LH2 experimental data has a large spread, leading to uncertainties which follow-through into modelling and analytical investigations.
- Basic fundamental data is needed in the following areas:
    - Experimental data around the critical point.
    - Transient systems, multiphase flows, and data gathered around phase change boundaries.
    - Heat transfer coefficients, particularly in boiling and phase change.
    - Behaviour of LH2 in relation to surfaces including wetting/dynamic contact angle, adsorption, permeability, thermal conductivity, and magnetic influence.
- Applied experimental data and associated accurate models are needed in the following areas:

- Multiphase transient applications, including cavitation and sloshing.
- Ortho- para-hydrogen conversion in the presence of catalysts and within dynamic scenarios.
- Vapour-Liquid interface behaviour, including energy and mass transfer in dynamic scenarios.
- Supercritical flow within pipe systems, including through valves and pumps.
- Impact of large pressure or thermal gradients on LH2 multiphase flow.
- Impact of acoustics, vibration, and electro-magnetic fields on LH2 supercritical and multiphase flow.
- Impact of slush hydrogen or frozen gases within LH2 on flow with practical fuel systems.

Simulation tools are reliant on fundamental properties and are therefore impacted by the lack of basic fundamental data, as well as the lack of applied experimental data. Modelling approaches have been developed from 1D network approaches to high fidelity CFD. However, as validation data is sparse this has impacted the accuracy of these simulation tools.

Experimental data on fundamental research is a building block on which the development of models and more complex experimental data can be gathered. No significant gaps have been identified in experimental design and sensing equipment, aside from the need for more robust and accurate sensing instrumentation for liquid hydrogen.

Key Areas for Investment

- Experimental facilities which operate with LH2 under clearly standardised methodologies will allow robust experimental data to be gathered.
- A skilled workforce, both from an academic and technical background, is vital to enable these facilities to be designed and operated safely.

Interdisciplinary Links and Shared Gaps

This work has been undertaken alongside similar work to identify the low-TRL landscape on LH2 materials and health and safety research. Some of the gaps identified in this document link closely with these themes. These interdisciplinary gaps include:

- Effects of LH2 on surfaces and *vice versa*, particularly in relation to boiling and supercritical flow. Surface finishes and molecular interactions with hydrogen link with thermofluids properties such as wetting behaviour, vapour pressure and surface tension.
- Tribology, which links thermofluids properties such as viscosity and compressibility, as well as materials properties including behaviour at cryogenic temperatures and susceptibility to hydrogen attack.
- Work and cavitation; cavitation can result in damage to surfaces and materials due to sudden and unexpected changes in pressure.
- Unwanted leakage and dispersion in the case of accidental releases. Fundamental LH2 thermofluid properties will affect the consequences of LH2 releases.
- Boiling Liquid Expanding Vapour Explosions, that are explored in the health and safety report, require understanding of the multiphase thermofluids behaviour of LH2.

Contents

1. Introduction

The Aerospace Technology Institute (ATI) FlyZero project concluded that liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft. Amongst the many reports published, FlyZero identified a UK gap in liquid hydrogen capability. At the same time, the ATI published the UK aerospace technology strategy, Destination Zero, which identified that the UK could grow its market share from 13% to nearly 18% by 2050, as aircraft fleets transition towards zero-carbon emission technologies.

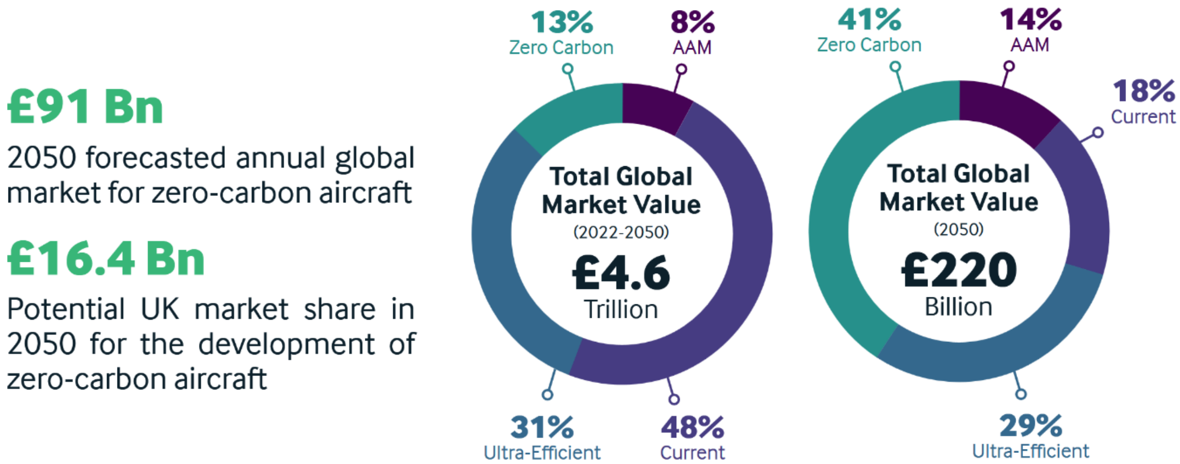

FIGURE 3: ATI PUBLISHED GLOBAL MARKET PROJECTIONS

Although the date for realising this market projection is likely to be later than currently published, the potential opportunity for hydrogen aircraft remains. Achieving this market share is contingent on continued investment in technology development, regulation, and infrastructure. Having identified that other countries are already planning, or have commissioned, facilities and initiatives to support their domestic supply chain, in 2023 the ATI set up the Hydrogen Capability Network (HCN).

The HCN project aims to make recommendations on strategic interventions and what is required to maximise UK industry competitiveness in the emerging liquid hydrogen-powered flight market. Over the past 24 months, the HCN team has connected with over 260 stakeholders from across the UK. This has included 90+ face-to-face discussions and site visits; and over 100 attendees from 44 unique organisations to our testing, research, and skills workshops. The HCN ran a UK Cryogenic Hydrogen Research Conference in January 2025, with over 150 attendees from academia and industry.

1.1. Report Scope

This report was completed for ATI HCN to provide a global landscaping study documenting Liquid Hydrogen (LH2) low TRL (1-3) research in Thermofluids. The focus was on research beyond that taking place in the United Kingdom. Where key capability and publications were from the UK these have been included within this report.

There are separate reports to document the global landscapes for Cryogenic Hydrogen Health and Safety and Materials Behaviour in Cryogenic Hydrogen Environments .

The ATI HCN commissioned this work to enable the identification of global research gaps to ensure that future research strategies across the UK met remaining gaps and was synergistic with the global landscape rather than repeating existing research. This report should invite further discussion with the ATI from industry and academia on how thermofluids research can be progressed through the ATI programme or through other funding channels which support fundamental research.

This report provides summaries of found information relating to low TRL research in Thermofluids for all regions except the UK. Low TRL research here meaning fundamental engineering science, not low TRL technology development although section 14 does provide some commentary on scenarios which pulls in technology information. Where seminal references are from the UK these have been included but otherwise the review has focused on research from outside the UK.

Section 1.2 explains the terms (metadata) used to classify the search, section 1.3 provides a brief description of the methodology employed and section 1.4 provides an introduction to hydrogen classification. Sections 0 onwards summarise information under the secondary metadata headings.

1.2. Metadata

The metadata themes that were defined for Thermofluids at the beginning of the project were set from a series of workshops undertaken with stakeholders by the ATI HCN. The reports summarising these workshops are available from the ATI website (Hydrogen Capability Network - Aerospace Technology Institute).

The defined themes were:

- Hydrogen characterisation for heat transfer behaviour i.e. heat transfer coefficients of relevance through systems, critical point/supercritical behaviour, heat exchanger design, stratification.
- Hydrogen characterisation for flow behaviour i.e. compressibility, cavitation, dynamic wetting behaviour/surface interaction, impact of vibration, material catalytic behaviour, fluid worked behaviour in components and systems, sloshing, tribology.
- Hydrogen characterisation in the presence of electro-magnetic fields, i.e. static discharge, impact on para or ortho balance.
- Hydrogen critical point or supercritical research.
- Impact of contaminants in liquid hydrogen.
- All past and active research infrastructure enabling liquid hydrogen experimental work, at all scales, will be listed. Ensuring that all current experimental infrastructure globally can be identified, much of this has been mapped already but the current information is fragmented and there is a need to pool all of this.
- Bespoke modelling techniques or design tools for liquid hydrogen, with particular focus on reported robustness, resilience and validation/verification of those tools.
- Best practice information regarding purging, refuelling/defueling, inspection, maintenance, venting.

On review by the ATI HCN team and industrial advisory board on 15th October 2024 these were amended to include a secondary level of granularity for topics. The second level list of 15 topics have been used as section headings within this report.

1.3. Methodology

Information was collected by using database search engines which pull back publications across 30 different media types including academic journals and conferences, textbooks, reports, patents, datasets and newspapers. This information was reviewed, and the main TRL research outputs were analysed in sections 0-14 below.

From the collected data the trends on publications shown in figures 4 and 5 were captured. Figure 4 shows the publication count from 1951 to 2025 by decade for liquid hydrogen fluid properties publication in the engineering field. Whilst this does not cover the whole Thermofluids research area it provides a good guide to the trends in publications in liquid hydrogen low TRL Thermofluids which quadrupled between the decade from 2001 to the decade from 2011.

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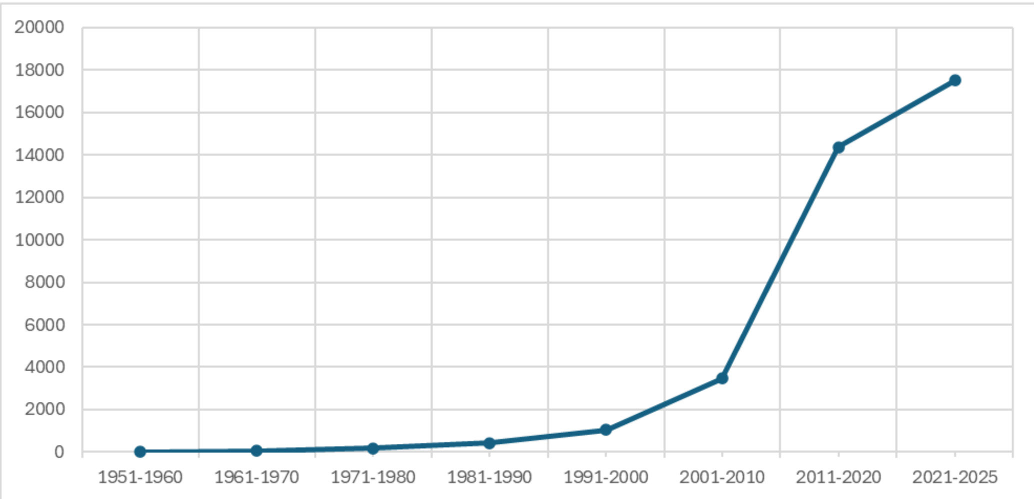
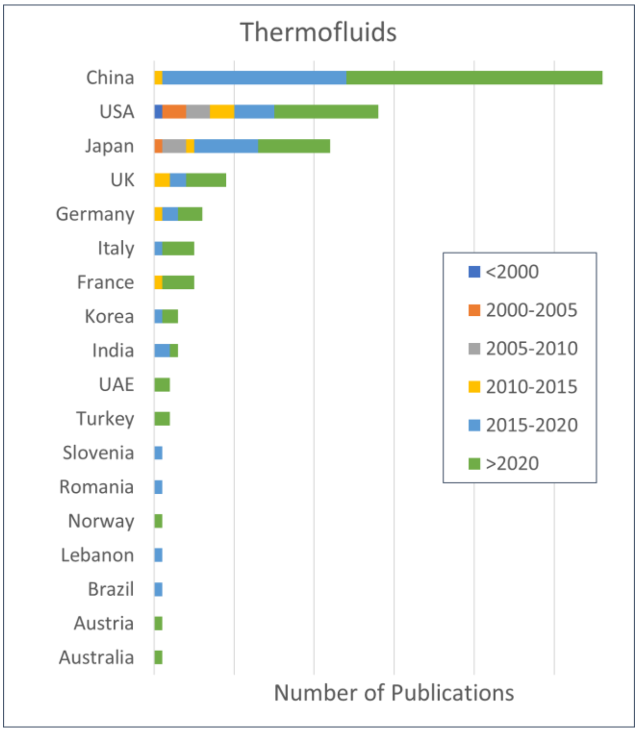


FIGURE 4: LOW TRL RESEARCH PUBLICATION COUNTS IN ENGINEERING LIQUID HYDROGEN FLUID PROPERTIES BY DECADE



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1.4. Hydrogen Classification

Hydrogen is the first element on the periodic table with a standard molecular weight of 1.007. At standard temperature and pressure, it is the lightest and smallest element. Hydrogen has three isotopes (hydrogen, deuterium, and tritium); for the duration of this report, 'hydrogen' will refer to the most common isotope which comprises one proton and one electron.

Hydrogen exists in various forms, classified based on its molecular structure or its physical state. Hydrogen's most common form is a gas (GH2). Gaseous hydrogen and hydrogen vapor both refer to hydrogen in a gaseous state, but they have distinct meanings based on thermodynamic definitions. Gaseous hydrogen is hydrogen in its natural state at standard temperature and pressure, existing as a diatomic molecule (H2). It remains in a gaseous state above its boiling point of approximately 20K at atmospheric pressure. In two-phase flow or in a saturated system, multiple phases of hydrogen, such as liquid and gaseous, are present. When cooled below 20K, gaseous hydrogen becomes liquid hydrogen (LH2). Under extreme conditions, hydrogen can transition into solid hydrogen, slush hydrogen (solid-liquid hydrogen), or a supercritical fluid.

Liquid hydrogen (LH2) is a cryogenic fluid with a low liquid density (its specific gravity is approximately 0.07), requiring highly insulated storage tanks to prevent rapid evaporation. Due to its high energy content per unit mass, liquid hydrogen is commonly used as rocket fuel, in cryogenic research, and as a potential fuel source for hydrogen-powered vehicles and energy systems. The numerous opportunities and sectors in which LH2 can be used as a fuel or energy carrier are a key contributing factor to the increase in publications as seen in Figure 4. Handling and using liquid hydrogen presents challenges such as extreme cold temperature, vaporisation, flammability, as well as the potential for detonation. The thermofluid fundamental properties considered in this document therefore link closely with the low-TRL investigations into health and safety (H&S) as seen in the Cryogenic Hydrogen Health and Safety Global Research Landscape report.

Figure shows a phase diagram for hydrogen with density as a function of temperature and pressure; the transition to supercritical fluid can be seen above the critical point.

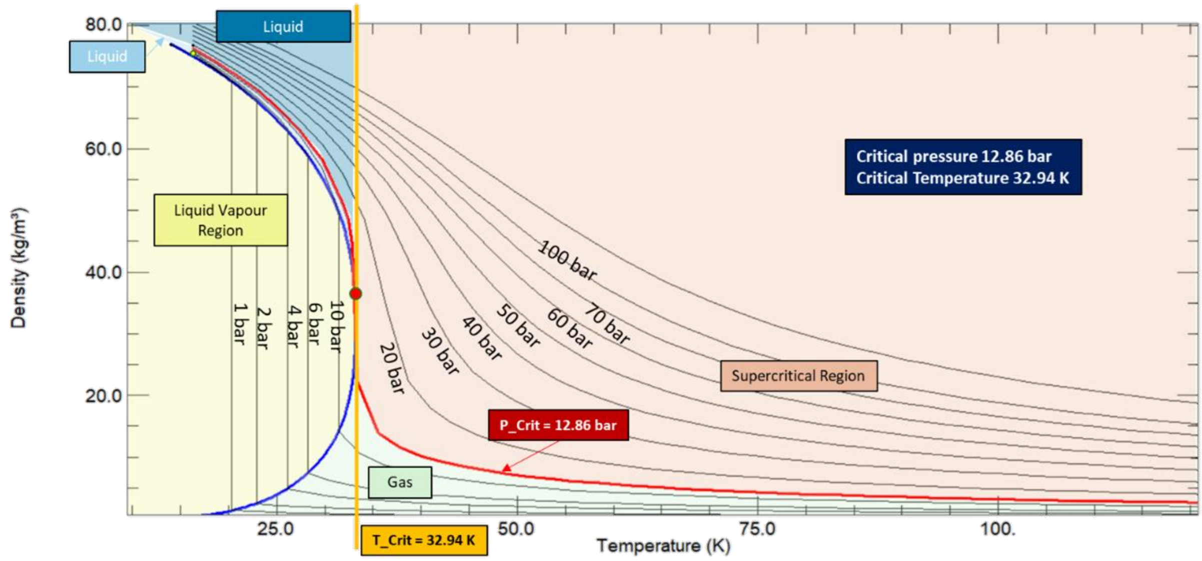

FIGURE 6: PHASE DIAGRAM FOR HYDROGEN, FROM FLYZERO REPORT FZO-PPN-REP-0024, GENERATED FROM REFPROP (LEMMON ET AL.)

Liquid hydrogen and supercritical hydrogen are two different physical states of hydrogen with distinct properties. Supercritical hydrogen exists when hydrogen is subjected to temperatures and pressures beyond its critical point, which is at approximately 33 K and 1.3 MPa. When hydrogen is in its supercritical state, it no longer behaves distinctly as a liquid or gas but instead exhibits properties of both. In this state, supercritical hydrogen has a density closer to a liquid while maintaining the diffusivity and viscosity of a gas. As hydrogen approaches the supercritical area, properties of different phases such as density and compressibility change more rapidly, and their values as well as sensitivities need to be understood.

Figure shows the two-phase liquid and vapour region; this area is of interest for many industrial LH2 systems as the fluid may pass through this region from its point of storage to its point of use. The transition region to a supercritical fluid is also relevant for many systems; for example, supercritical hydrogen is expected to be used in aerospace gas turbine combustion. Therefore, the properties of hydrogen in the transition regions of the phase diagram need to be understood.

From a molecular perspective, hydrogen has two spin isomers: ortho-hydrogen and para-hydrogen. In ortho-hydrogen, the two hydrogen nuclei (protons) have parallel spins, while in para-hydrogen, the spins are antiparallel. These isomers differ in energy, with ortho-hydrogen being the higher-energy form and para-hydrogen the lower-energy form. Ortho-hydrogen is dominant at higher temperatures, while para-hydrogen becomes more prevalent at very low temperatures, such as in liquid hydrogen. The ratio of ortho- to para-hydrogen is typically 3:1 at room temperature but shifts toward more para-hydrogen at lower temperatures. This 3:1 room temperature ratio is sometimes referred to as 'normal' hydrogen. The difference in spin configuration affects hydrogen's physical properties, such as heat capacity and its behaviour in cryogenic and energy applications. The ratio of ortho-para isomers in liquid hydrogen is of importance as a non-equilibrium ratio will experience energy changes due to conversion until an equilibrium is reached.

Multiphase flow in fluid dynamics refers to the simultaneous flow of two or more distinct phases, such as gas-liquid, liquid-liquid, or solid-liquid (e.g., solid particles are dispersed in a continuous liquid), which interact with each other while maintaining separate phases. Multiphase flow of hydrogen occurs in various scenarios, including cryogenic liquid hydrogen boiling, bubble formation during cavitation, two-phase pipeline transport, slush hydrogen flow, and hydrogen leakage.

Slush hydrogen, which is the mixture of solid hydrogen with liquid at the triple point (13.8 K and 0.007 MPa), has been mooted as a potential approach for long term storage for hydrogen. Park et al., 2024 [1] experimentally investigated slush hydrogen at the triple point in a ratio of 47% solid and 53% liquid and measured an 15% increase in density compared to liquid hydrogen.

For a high-level overview of LH2 physical and chemical characteristics, Aziz has a review on LH2 [2] [Aziz 2021], or the PRESLHY handbook of hydrogen safety has a helpful overview in its LH2 chapter [Verfondern 2021] [3].

2. Ortho-hydrogen and Para-hydrogen

2.1. Overview

Ortho-hydrogen and para-hydrogen are the two distinct spin isomers of molecular hydrogen. These isomers have different nuclear spin states, which result in differing physical and quantum properties.

Molecular hydrogen occurs in two isomeric forms, one with its two proton nuclear spins aligned parallel (ortho-hydrogen), the other with its two proton spins aligned antiparallel (parahydrogen). These two forms can be called *spin isomers*. For further details Leachman et al. (2025) [4] is recommended.

The amount of ortho- and para-hydrogen varies with temperature:

- at zero Kelvin, hydrogen contains mainly para-hydrogen which is more stable.
- at the temperature of liquefaction of air, the ratio of ortho- and para-hydrogen is 1:1.
- at room temperature, the ratio of ortho- to para-hydrogen is 3 :1.

Given that hydrogen tends to be in para form at temperatures below equilibrium temperature (− 193 ◦C), ortho-hydrogen spontaneously converts into para-hydrogen, in an exothermic reaction. The ortho-para conversion enthalpy rises with decreasing temperature, whilst the ideal gas enthalpy of LH2 (across all ortho-para ratios) decreases. The latent heat of vaporisation is 448.7 kJ/kg at the normal boiling point, whilst the heat of the ortho-para hydrogen conversion is 702.98 kJ/kg (Leachman, 2025 [4]). The ortho-para hydrogen conversion enthalpy decreases by an order of magnitude between 20K and 300K.

If hydrogen is not converted into para-hydrogen before being liquefied by a catalytic process, the heat generated by the ortho-para conversion (OPC) can cause most of the liquid hydrogen produced to evaporate. For more detail, the reader is advised to see reviews by Fukutani (2013) [5], Jiao (2024) [6], Leachman (2009) [7], and Xu (2024) [8].

2.2. Key Research Gaps

- A large number of academic papers are experimental, unlike in most other fields with LH2. However, there is still a need for a more comprehensive and fundamental understanding of the spin conversion causes when affected by catalysts and other activation mechanisms.
- Despite a large amount of work on ortho-para hydrogen, there is a lack of a universal kinetic model for the catalyst-assisted conversion reaction, hindering the development of accurate predictive models for ortho-para conversion reactors; this includes quantitative descriptions of cooling requirements and system pressure loss (Jiao, 2024 [6]).
- Research focussed on understanding ortho-para hydrogen conversion is limited, partly due to its multidisciplinary nature. Research of nuclear spin isomers lies at the intersection of multiple scientific disciplines, including surface and solid-state physics, molecular spectroscopy, magnetism, thermodynamics, chemical kinetics, and the study

of irreversible processes. This demonstrates the need for research groups with researchers with a wide spectrum of knowledge.

2.3. Key Research Groups

Institution	Country	Topic
CSIRO (Falcao et al., 2024 [9]; O'Neill et al., 2023 [10])	Australia	Ortho-para hydrogen conversion (OPC) kinetics, process optimisation and catalyst development for hydrogen liquefaction.
University of Western Australia (Falcao et al., 2024 [9]; O' Neill et al., 2023 [10] – collaboration with CSIRO)	Australia	Experimental and numerical capabilities for hydrogen liquefaction processes.
Zhejiang University, Hangzhou (Haoren et al., 2024 [11]; Shi et al. 2023 [12]; Teng et al. 2023 [13]; Zhu et al., 2023 [14, 15])	China	Large amount of numerical work. All work is only validated against literature from the past; however, a large number of people are working in this group doing research on OPC; this includes OPC in OP converter, heat exchanger, liquefier.
TU Dresden & Forschungszentrum Jülich (Eisenhut et al., 2020 [16]; Hannot et al., 2024 [17])	Germany	Hydrogen liquefaction and OPC, development of energy-efficient systems for hydrogen storage. Speed of Sound for different ratios of ortho-para LH2.
University of Tokyo (Fukutani et al., 2013 [5])	Japan	Physisorption, kinetics of the OPC on various surfaces, often on Silver.
Washington State University (Leachman et al., 2009 [7]; Bahrami et al., 2014 [18])	USA	Fundamental properties of OPC; also research of various topics on LH2.

2.4. Narrative

In recent years, ortho- to para-hydrogen conversion has emerged as a prominent area of study, reflecting its high relevance, with more than half of the papers listed having been published in the last two years.

The study of ortho- and para-hydrogen involves several disciplines, such as quantum mechanics, material science, cryogenics, and energy systems. Overall, recent research on hydrogen conversion relates to basic concepts, measurement methods and materials involved in the hydrogen research and development activities (Ilisca, 2021 [19]).

The main subtopics of research on hydrogen conversion are:

- Quantum physics: understanding the quantum states and properties during and after spin transitions between ortho and para states and their effects on thermodynamic and quantum systems. Spectroscopic techniques are employed to differentiate and quantify ortho and para forms.
- Thermodynamics: conversion dynamics and reaction kinetics: equilibrium ratios; catalysts for conversion; cryogenic efficiency; ortho-para concentration ratio; conversion rate/speed/etc.
- Design configurations affected by ortho-para hydrogen: stability of the ortho- and para-hydrogen in various conditions; exothermic conversion process (ortho to para) during hydrogen liquefaction.
- Nuclear Magnetic Resonance (NMR), imaging applications and magnetic adsorption: hyperpolarised parahydrogen; spin manipulation in diagnostic and therapeutic technologies.
- Material interactions: how ortho-para hydrogen interacts with metallic surfaces, catalysts and various nanomaterials. Use of various nanomaterials to control ortho- para-hydrogen ratios and improve catalytic efficiencies.

The first three subtopics have been extensively studied, especially in recent years, whilst the remaining two have been studied less extensively and these overlap with subjects covered in Sections 6 and 0.

Over the last few decades, theoretical and experimental investigations on hydrogen physical conversion were performed over magnetic catalysts. New phenomena involve processes on non-magnetic catalysts (Ilisca et al., 2021 [19]).

Historically, most measurements of hydrogen spin isomers were macroscopic, focusing on the overall concentrations of isomers, often employing static techniques. Modern methodologies, have shifted towards dynamic, radiative measurements across a range of frequencies, including infrared (IR), ultraviolet (UV), and radio waves (Ilisca et al., 2021 [19]).

A pivotal development occurred in 2003, when Fukutani et al. (2003) [20] employed the REMPI (Resonance Enhanced Multi-Photon Ionisation) method, using UV radiation to monitor the time evolution of spin isomer conversions. Fitzgerald (2006) [21] enabled the near-continuous tracking of absorption lines for individual isomers in real time by utilising IR spectroscopy. These advancements have significantly improved the capacity to analyse hydrogen spin isomers dynamically and precisely.

The rapid advancement of terahertz (THz) technology is also beneficial for hydrogen research as it can be used for safely detecting hydrogen leaks and monitoring storage systems in real time. THz radiation coincides with the fundamental frequency of ortho-para hydrogen conversion (around 3 THz, Ilisca et al., 2021 [19]).

3. Fundamental Fluid Properties

3.1. Overview

The following fundamental properties of liquid hydrogen (LH2) and supercritical hydrogen are in scope of the current review: density, viscosity, compressibility, thermal conductivity, thermal expansion, dielectric constant, surface tension, vapour pressure and heat transfer coefficient. These fundamental properties have been reviewed as they frequently form the building blocks for more detailed experimental and modelling developments, such as scenarios or component design. However, they also overlap with each other as frequently knowledge of one or more of these properties is needed to measure others; experimental sensing and design is covered in Section 0. This chapter includes an overview of key reviews on multiphase flow related to liquid hydrogen, while specific aspects of fluid dynamics are covered in other chapters. It also highlights emerging research topics, existing gaps, and leading countries and Institutions in the field.

The vast majority of experimental data gathered on the fundamental properties of LH2 and supercritical hydrogen occurred in the twentieth century as part of the space race. The NIST database is a repository for this data and is the widely accepted standard for model development or new data comparison. As such, this section will not delve into detail on the original experimental data sources; these can be found through interrogation of the NIST database. Whilst there are likely to be gaps and overlaps in this reference experimental data, detailed analysis of it is outside the scope of this review. Leachman et al. (2009) [7] reviewed a considerable amount of historical data and developed fundamental equations of state which have relevance to multiple fundamental properties reviewed in this section.

Given the nature of the review there are overlaps with multiple sections within the report, particularly with sections 0 (Ortho-Para) and 0 (Heat Transfer). Section 0 which reviews sensing and control, and section 12 which reviews experimental design/proxy fluid low TRL research provides more information on the challenges faced in experiments.

Key issues arising in researching the properties of LH2 include the scarcity of recent experimental data, challenges in measuring properties at cryogenic temperatures, and the complexity of validating theoretical models against limited historical data.

Papers recommended for more detail are Leachman et al. (2007) [22], Sakoda et al. (2010) [23] and Ikeuba et al. (2024) [24]. A useful summary of properties is also provided in a report by Choi et al. (2004) [25] . For multiphase flow, recommended sources for further reading include Wang et al. (2024) [26]) and Ratnakar et al. (2021) [27]. Specifics on supercritical hydrogen can be found in Dziedzic et al.(1993) [28], Locke et al.(2005, 2008) [29, 30], Pizzarelli et al. (2018) [31], Ribert et al. (2015) [32]. Locke's papers (NASA) combine fundamental properties from earlier studies from the 1960s, with the authors justifying their inclusion due to the availability and broad range of fluid conditions covered in those papers.

3.2. Key Research Gaps

Overall, there is limited data (whether experimental or analytical model based) on fundamental properties of low-temperature LH2; the majority of experimental data used and referenced in modern papers dates back to the mid twentieth century. Boiling and phase change is an area where there is a large volume of literature, Section 0 includes reviews on specific heat transfer aspects.

Key gaps include:

- Experimental measurement and data of the listed fundamental properties, particularly using modern sensors and consistent experimental design to minimise uncertainty and data scatter. More experimental information on the following fundamental properties is of particular interest:
    - Viscosity.
    - Vapour pressure, including the vapour-liquid interface.
    - Surface tension (which links with the vapour-liquid interface).
- Experimental data at phase change boundaries and in complex flows.
    - Behaviour of fundamental properties in dynamic systems varies from that of static systems, the latter of which form the basis of most historical experimental design.
- Multiphase behaviour of liquid hydrogen when encountering sudden expansions, large pressure or thermal gradients, including transient behaviours at points of change.
- Combined experimental and modelling analysis of system/component level analysis to provide methodology development, validation data and to enable monitoring and control approaches to be investigated.
- Experimental studies of alternative low energy liquefaction approaches, providing validation data for modelling.
- The behaviour of hydrogen near and at the critical point is not well characterised, including the transition dynamics between liquid, gaseous, and supercritical states.
- Supercritical hydrogen is known to penetrate materials more readily than gaseous hydrogen. The interaction between supercritical hydrogen and relevant materials requires further experimental investigation.

It is challenging to gain accurate experimental measurements of the fundamental properties of LH2 due to its extremely low temperature, rapid evaporation, and the difficulty in maintaining stable conditions for accurate data acquisition. However, modern sensing techniques have improved accuracy and response/detection times than those which were used in the mid twentieth century. While some data exists from the 1950s to the 1970s (e.g. Hoge et al., 1951 [33], Webeler et al. 1961 [34] , Blagoi et al. 1966 [35], Briggs et al. 1975 [36]), there is limited recent research specifically on fundamental properties of LH2 aside from aspects relating to heat transfer and phase change.

3.3. Key Research Groups

The table below lists research institutions that have contributed to the study of LH2 fundamental properties post 2000. The most active countries and institutions in recent years are identified below, based on observations from the papers in scope for this project and information from the bibliometric literature on related subjects.

Strong collaborations are found between USA, Europe, India and China. Fewer (but still significant numbers) of collaborations are observed for countries such as Australia, Japan, UK and Canada.

Institution	**Country**	**Topic**
Chinese Academy of Science	China	Largely numerical studies, often incremental and with small variation of specific parameters. Additionally analytical studies and reviews exist. Number of published papers from China is growing exponentially, unlike other countries where research interest growth is more gradual.
Japan Atomic Energy Agency (JPARC) (Horie et al., 2015 [37])	Japan	Characterisation of supercritical hydrogen moderator on JPARC neutron spallation source; focus on heat transfer and density characteristics.
Kyushu University, Kyoto University (Sakoda et al., 2010 [23])	Japan	Their research is typically connected to marine shipping possibilities of LH2 and improvements of their technologies; often they perform quite unique but complex experiments.
Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), National Institute of Advanced Industrial Science and Technology (AIST), Fukuoka (Sakoda et al., 2010 [38])	Japan	Research facilities specially designed for high-pressure hydrogen experiments up to 100 MPa. Has a wide range of research – from fundamental research to full-scale commercialisation.
The Japan Aerospace Exploration Agency (JAXA) in Sagamihara (Horie et al., 2015 [39])	Japan	Investigations into supercritical hydrogen for space applications, including propulsion systems and storage technologies.
Russian Academy of Science	Russia	Analytical and experimental work, however few recent publications.
Lawrence Livermore National Laboratory (Petitpas & Aceves, 2013 [40])	USA	Focuses on advancing hydrogen technologies, particularly in cryo-compressed hydrogen storage, hydrogen production, and high-performance simulations to support the development of sustainable hydrogen energy solutions.

Institution	Country	Topic
NASA, including Glenn Research Center, Fluids and Cryogenics Branch, Cleveland, (Ganesan et al. 2024 [41])	USA	Heat and Mass transfer characterisation for cryogenic nucleate and flow boiling.
National Institute of Standards and Technology (NIST) (Bellur et al., 2022 [42])	USA	Generation of fundamental data, including phase change behaviour of LH2.
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL), School of Mechanical Engineering, Purdue University (Ahmad et al. 2024 [43])	USA	Heat transfer coefficient and critical heat flux database and correlations.
Sandia National Laboratories	USA	Studies into research and development methods to discover materials for hydrogen production, storage and use, evaluating their properties and performance.
The Georgia Institute of Technology (Ribert et al., 2015 [32])	USA	Has expertise in hydrogen research, including work on supercritical hydrogen; has been a partner with Siemens Energy developing hydrogen technologies focusing on hydrogen production, storage, transport, and utilisation.
University of Cincinnati, Cincinnati, OH, (Bellur et al. 2022 [42])	USA	Generation of LH2 liquid-vapour interfacial data and models, utilising neutron imaging.
Washington State University (Leachman et al., 2007, 2009 [7, 22])	USA	Fundamental properties of ortho-para hydrogen; research of various topics on LH2. Experimental and analytical studies of liquid hydrogen behaviour, including vapour-liquid research.

3.4. Narrative

There are several challenges to understanding the fundamental properties of LH2:

- Extreme low temperatures: LH2 exists at cryogenic temperatures (around 20 K), requiring specialised equipment and materials that can function reliably in such conditions, making measurements complex and prone to errors.

- LH2 and supercritical hydrogen have been observed to behave differently than expected in dynamic systems and the precise behaviour of hydrogen near and at the critical point is not fully understood. This includes the transition dynamics between gaseous and supercritical states, indicating that measurements of fundamental properties in flowing systems are needed.
- Instrumentation limitations: It is challenging to accurately measure thermal conductivity or viscosity due to LH2's unique low viscosity and high diffusivity properties.
- Low density and high volatility: LH2 has a low density and high volatility, which makes it difficult to maintain stable liquid phases for measurement over extended periods, especially as it evaporates quickly at higher temperatures.
- Pressure and phase behaviour variability: The properties of LH2 change significantly with pressure and phase transitions (e.g. from liquid to gas or solid), making it difficult to maintain consistent conditions for accurate measurement.

These challenges necessitate highly specialised experimental setups and careful calibration, which further complicate research in this area. The complexity of the experiments, therefore mean that there was a lack of consistent and high-precision experimental data, particularly at lower temperatures below 23 K, where most studies are limited or outdated, often from the 1950s–1970s. For example, Leachman et al. (2009) [7] found a wide scatter of experimental data relating to properties such as vapour pressure, density, virial coefficients, and more. More recently researchers have used different approaches, such as neutron imaging to generate new data sets for vapour-liquid equilibria and for phase change analysis. Section 0 reviews low TRL research in sensing and control and provides more information on the challenges.

Bell et al. (2023) [44] noted that the extremely low temperatures of cryogens limit the accuracy and availability of experimental thermophysical property measurements, particularly for transport properties. Traditional scaling methods, such as corresponding states theory, are known to be inaccurate for fluids with significant quantum effects. Their study investigates how quantum effects influence thermodynamics and shear viscosity in hydrogen, including LH2. Beckmüller et al., (2024) [45], extends this to investigate the impact of mixtures of LH2 with Argon, Helium and Neon.

Quantum calculations were conducted to determine the thermodynamic properties of normal hydrogen, ortho-hydrogen, and para-hydrogen as preliminary studies for numerical simulations, examining the impact of low-temperature phenomena on the rapid phase transition of liquid hydrogen (Salzano et al., 2020 [46]).

There is an overlap with heat transfer (section 0) and work (section 0). There is also an overlap with the Health and Safety topics of leakage, dispersion and ignition and an overlap with publications that can be found in the Ortho-Para Hydrogen section 2. For example, viscosity was covered in Hu et al. (2024) [47], where effect of viscosity and the flow rate was briefly discussed. In Leachman et al. (2009) [7], new fundamental equations of state were developed for para-hydrogen, normal hydrogen, and ortho-hydrogen, replacing existing property models. The quantum law of corresponding states was applied to enhance the accuracy of thermophysical property predictions near the critical region and in liquid state. Experimental data of LH2 properties (including density, heat capacity and vapour pressure) from multiple papers from the past was also included.

Phase change is reviewed within Section 4.5 heat transfer, in terms of boiling and flows of vapour-liquid hydrogen. Of particular note, is a collaboration between JAXA and Waseda University that has produced experimental data and models for liquid single phase, bubbly flow, intermittent flow and initial annular two-phase flow regimes (Sakamoto et al., 2023 [48]). Within the same section (4.5), a collaboration between NASA and Purdue University is also described, which has led to a set of very recent experimental and modelling papers.

Some experimental work on supercritical hydrogen is occurring at neutron experimental facilities such as JPARC, the European Spallation Source (ESS), and others , Aso (2006) [49], Horie (2015) [37], Klaus (2015) [50, 51] . Useful papers that provide a comprehensive review of the timeline of various property measurements are Sakoda et al. (2009) [52] and Bartolomeu (2020) [53]. The properties of these moderators are highly characterised and managed, which gives information on fundamental data for supercritical hydrogen, but detailed tables on the fundamental properties is not shown in associated papers.

At some point in transport and dynamic systems, the hydrogen will transition from being liquid to being supercritical. Fundamental experimental data and reliable thermodynamic models are needed at this intersection, but no information has been found beyond the NIST database. This lack of information was noted by Assael (2011) [54] in their numerical modelling of hydrogen thermal conductivity, which resulted in increased uncertainty around the critical point. Information at the triple point, which may be relevant for considerations of slush hydrogen or abnormal operating conditions, is also lacking.

Supercritical hydrogen will have different corrosive, embrittlement, and surface interactions to LH2. Materials interaction with supercritical hydrogen also needs to be considered. Some existing research covers supercritical hydrogen adsorption in nanomaterials, in particular nanotubes. This information will link with other materials work as detailed in the Cryogenic Hydrogen Materials Research Landscape report.

3.4.1. Density

Knowledge of hydrogen density in any phase is vital for system design and modelling, but it is also frequently a constant in measuring other fundamental properties, such as vapour pressure or the dielectric constant. Accurate density measurements have a follow-on effect on the wider characterisation of hydrogen properties.

Historical research on LH2 density has primarily focused on experimental measurements, such as those by Turney and Snyder (1969) [55], who used a capacitance density meter to study liquid and two-phase hydrogen flow. Leachman et al. (2009) [7] list a variety of density experiments, including some in the supercritical range; that work highlights the difficulty of measuring the density near the critical point. The density of supercritical hydrogen is found to be highly dependent upon both temperature and pressure (Merkle et al. 1998 [56]). More recently, the report "Liquid Hydrogen Properties" by Choi (2004) [57] provides an in-depth analysis of various properties of LH2, including its density. This report discusses the dependence of LH2 density on temperature.

Ohira (2004) [58] reported on the development of density measurement technologies for slush hydrogen. There is close agreement between measured and calculated densities, although recent advancements in this area remain limited.

Most recent research into LH2 and supercritical density focuses on modelling using molecular theory. Bartolomeu and Franco (2020) [53], developed density predictions for supercritical hydrogen (among other fundamental properties) from molecular simulations using data from the NIST database. Behnejad and Miralinaghi [59] have undertaken similar work. It would be useful to compare these works with independent experimental data.

3.4.2. Viscosity

Recent research on the viscosity of LH2 is limited. Studies from 1930s-1960s provide a wide range of experimental data, largely using capillary tube methods reporting viscosities about 10% higher than other techniques. In some cases, such as the work by Diller (1965) [60], a quartz crystal oscillator was used. Diller measured the viscosity of LH2 as well as supercritical hydrogen and hydrogen near the critical point. Some consideration of uncertainties is noted, particularly in relation to the fact that the viscosity measurements depend upon the measured density.

This experimental data, as well as that from other sources, is included in the NIST database. Beyond the NIST database, Leachman et al. highlight key experimental datasets from the twentieth century (Leachman et al. 2007 [22]); this paper also investigates the differences between calculated and experimentally gathered data for both density and thermal conductivity.

According to Bell et al. (2023) [61] , despite recent advancements, comprehensive and widely accepted viscosity data for LH2 remains scarce, highlighting the need for further investigation. Bell et al. (2023) [61] examined quantum entropic effects on the viscosity of LH2 providing insights into its thermodynamic and momentum transfer properties.

Equations of state, such as those discussed by Bell et al. (2023) [44], for viscosity are used in most higher TRL fluid models. There is also ongoing modelling work on hydrogen viscosity at a quantum level, such as that by Nagashima et al. (2011) [62] or Yang et al. (2024) [63]. This modelling work at a quantum level can be complementary to larger scale models and equations of state as well as improve understanding of hydrogen states at a fundamental level.

3.4.3. Compressibility

Compressibility refers to the ability to reduce volume under pressure. Like most liquids, LH2 is nearly incompressible due to the close molecular spacing. One example of its incompressibility is in the use of LH2 moderators at neutron source; for example, Klaus et al. (2015) [51] and [50] highlight that neutron heat loads in the moderators result in large pressure fluctuations due to LH2 incompressibility. Compression is possible for supercritical fluids and under high pressures, this property might be critical for designing cryogenic storage systems and ensuring structural integrity under varying pressure conditions. Introduction of a cryo-compressed vessel is briefly described in Durbin et al. (2013) [64].

First and second virial coefficient data is present in the NIST database and was reviewed by Leachman et al. (2009) [7], although these are only relevant for any gaseous or supercritical fluid experiments. Virial coefficients are linked with the compressibility of a fluid through its deviation from the ideal gas law. Experimental data specifically on the compressibility of liquid hydrogen beyond the inference from work such as that by Klaus et al. (2015) [50, 51] has not been found and may not be necessary as the incompressibility estimation is suitable for industrial purposes.

Papers on hydrogen compressibility generally discuss compression of gaseous hydrogen (e.g., Orlova et al., 2023 [65]) and often at high temperatures. However, some cover hydrogen properties in a wider scope of parameters including low temperatures (e.g., Goncharov et al., 2013 [66]). Merkle et al. (1998) [56] give some information on supercritical hydrogen density and compressibility as part of modelling analysis; the paper mentions that supercritical hydrogen is a compressible fluid. There is also a link between supercritical compressibility and the sensitivity of the fluid's density to temperature and pressure fluctuations.

Goncharov et al. (2013) [66] reported that research gaps remain as a result of a lack of experimental data and the need to validate these theoretical approaches against observations with low-temperatures being particularly complex.

3.4.4. Thermal Conductivity

The thermal conductivity of LH2 varies with temperature and pressure. This property is essential for modelling heat transfer in cryogenic systems and understanding boil-off dynamics in storage applications. Leachman et al. highlight key experimental datasets from the twentieth century (Leachman et al. 2007 [22]).

There are limited recent experimental or modelling studies, with most research focusing on insulation materials. Assael et al. (2011) [54] developed representative equations for hydrogen thermal conductivity, and their paper references multiple experiments, including those at cryogenic temperatures. Most papers on LH2 thermal conductivity are from the late 1950s to 1970s, with a more recent paper by Charignon (2008) [67]. Roder (1970) [68] offers extensive experimental data on the thermal conductivity of both gaseous and LH2, including normal (where normal is taken to mean a hydrogen composition of 75% ortho-hydrogen and 25% para-hydrogen) and para-hydrogen. Charignon et al. (2008) [67] noted that while the thermal conductivity of subcooled LH2 has been reported in earlier studies, data below 23 K, and especially at 15 K, is extremely limited or non-existent. This data is essential for accurately calculating heat transport processes, such as temperature distribution within storage containers. According to their findings, experiments involving high-precision measurements of the thermal conductivity of subcooled LH2 in this temperature range have not been conducted. In their paper, Charignon et al. (2008) [67] present new measurements of the thermal conductivity of (isomer state) equilibrium LH2, taken between 15 K and 23 K and at pressures up to 1 MPa. The topic Thermal Conductivity is also related to Chapter 0 on Heat Transfer.

Locke and Landrum (2005) [69] and (2008) [29] investigated heat transfer correlations for supercritical hydrogen with some numerical modelling work; in these, they reference McCarty and Weber (1972) [70] for the their value of the thermal conductivity constant. No other experimental information on this constant has been found for supercritical hydrogen.

3.4.5. Thermal Expansion

The thermal expansion of LH2, a measure of its volume change with temperature, is significant near its boiling point of 20.3 K. Understanding this property is crucial for safe storage and accurate volume control in cryogenic applications, and it links closely with density variations in liquid and supercritical states.

Research on the thermal expansion of LH2 is scarce, with only a few related papers found. Older literature, including a paper by Schwalbe & Grilly (1984) [71] provides a study on LH2 thermal expansion, comparing measurements between 18.8–22.2K. Thermal expansion at low temperatures was shown to be sensitive to both pressure and temperature; even small temperature increases can cause significant volume expansion. Merkle et al. (1998) [56] also highlight that supercritical hydrogen has a high level of thermal expansion. This poses storage challenges, especially in rigid containers, where expansion may lead to dangerous pressure buildup. Consequently, LH2 storage systems are designed to account for thermal expansion to mitigate safety risks. As a result, in recent papers, thermal expansion is considered, such as in papers regarding LH2 tank technology development (Drube, 2024) [72] or LH2 safety assessments (Petitpas & Aceves, 2013 [73]).

3.4.6. Dielectric Constant

The dielectric constant of hydrogen is vital for capacitance measurement techniques, which are being investigated for use in level and flow sensing. The dielectric constant is dependent upon density as well as hydrogen spin state. A significant difference in the dielectric constant between hydrogen phases results in the ability to identify and quantify phases and phase changes in complex systems.

Publications from the 1920s through 1940s investigating the dielectric constant of hydrogen have been found, such referenced in Turney and Snyder's paper on LH2 density measurements (Turney and Snyder, 1969 [55]). Corruccini (1962) [74] summarised the experimental investigations of the dielectric constant of LH2; he references previous experimental investigations in gaseous, liquid, and solid hydrogen. Pashkov and Lobko (1980) [75] also undertook experimental investigations of ortho- and para- LH2. These experimental datasets have been used to develop correlations and models used in subsequent analytical and modelling work. Liu and Chow [Liu and Chow 1987] [76] used the dielectric constant to measure hydrogen density in liquid and gas phase.

No experimental information has been found in which the dielectric constant of supercritical hydrogen was investigated in the same manner as Corruccini [74] or Pashkov and Lobko [75]; this could be a key area for investigation. Furthermore, no information has been found on dielectric measurements in transient systems. As knowledge of the dielectric constant is vital for capacitance measurements, which are being investigated for LH2 flow and level measurements (including in transient systems), this lack of information is a gap which would benefit from being addressed.

3.4.7. Surface Tension

Within section 0 the impact on surface tension caused by contaminants and fluids mixtures is reviewed.

The surface tension of LH2 relates closely to phase change and multiphase systems. As the formation of bubbles in multiphase flow is a key consideration for LH2 systems, it is important to know the surface tension of LH2 at different points in the phase change diagram. Alternatively, the surface tension of a fluid can be calculated through its linear relationship with the bubble point.

Little information on the original experimental work to determine the surface tension of LH2 has been found, although Hartwig et al. (2014) [77] references works stating that it is between 2 – 12 mN/m. These values are considered low; in comparison, kerosene has a surface tension approximately an order of magnitude higher. This data is in the NIST database, which is frequently used for modelling or design purposes. Briggs et al. (1975) [36] carried out a review on surface tension (as well as viscosity and density) measurements, and highlighted that significant experimental work came from the USSR in the 1960s. Experimental work by NASA on bubble point tests Hartwig [77] and [78] link closely with surface tension, but more modern experimental measurements (including any that have occurred in the 21st century) have not been found.

Modelling work to calculate the surface tension of liquid hydrogen from molecular simulations has been undertaken by Zhao et al. (2004) [79], but the modelled values and the experimental values did not match. The paper indicates that the experimental values may be incorrect; however, no other papers have been found investigating this discrepancy.

Numerical papers which use surface tension as part of their models (such as Zheng et al. 2019 [80]) assume a constant surface tension value.

The lack of modern experimental information is an information gap, although the work by Hartwig et al. indicates that experimental work into bubble formation can rely on the existing data. This lack of experimental information may be a gap which requires further investigation; however, further model comparison and experimental work in two phase flow systems more generally will inform whether or not more experimental and component model detail on LH2 surface tension is needed.

3.4.8. Vapour Pressure

Whilst this review is for liquid hydrogen the vapour-liquid equilibria is of key importance in fully understanding the two-phase phenomena found within fuel systems. The key data set that is commonly used is the NIST data base “Thermophysical properties of fluid systems”. Analysis of much of this data can be found in Leachman et al. (2009) [7].

Within Boryaev et al., (2022) [81] a different approach is described where the link between the mass, pressure and temperature of vapour above liquid hydrogen within a store is determined experimentally and compared to theoretical predictions. The dynamics of filling and emptying a store within a fuel system are analysed, with a note that during drainage at pressure change rates higher than 1000 Pa s^{-1} the vapour content in the boiling liquid increases.

Bellur et al., (2022) [42] used neutron imaging to track the liquid-vapour interface for liquid hydrogen and methane. Two publications provided data Bellur et al., (2022) [42] and analysis Bellur et al., (2022) [42]. Modelling work by Bellur et al., (2023) [82] highlighted that the assumption that the liquid-vapour interface was at a uniform temperature during phase change was invalid. By using a local liquid temperature and pressure, experimentally defined mass accommodation coefficients for hydrogen show no sensitivity to container size, material or evaporation rate. This recent set of experimental papers indicates that there are still fundamental aspects of the vapour-liquid interface that are not fully understood.

Practical applications of the need to understand the vapour pressure can be seen in Ganesan et al., (2024) [41], where a two-phase frictional pressure gradient correlation for saturated cryogenic flow boiling is provided.

Sections 0 and 0 cover heat transfer and work, both of which link to vapour pressure.

3.4.9. Heat Transfer Coefficient

Section 0 looks at depth in the research investigating the heat transfer coefficient and the critical heat flux, including boiling. Here, a short summary is provided of the recent research.

Whilst single phase cryogenic fluid flow and heat transfer are regarded as well-predicted, with errors below 20% (Hartwig et al., 2024 [83]) , there is a research gap in two phase fluid flow and heat transfer. The values of heat transfer coefficients used within cryogenic design codes (e.g. SINDA/FLUINT) do not correctly predict cryogenic flows through pipework, including quenching and heating configurations (Mercado et al., 2019 [84]). The pressure drop associated with those flows are also incorrectly predicted. Horie et al. (2015) [37] measured heat transfer coefficients in supercritical fluids and found that the current correlation modelling methods show good agreement with the experimental data

Experimental research is very active in this area, often labelled as flow boiling within pipes (Ganesan et al., 2021 [85]). Numerical models are using these recent publications to validate codes, including a recent publication to draw together experimental data (Hartwig et al., 2024 [83], (LeClair et al., 2024 [86]).

4. Heat Transfer

4.1. Heat Transfer Overview

This section of the report has focused on heat transfer coefficient (HTC) and critical heat flux (CHF) of liquid hydrogen across natural convection, nucleate, flow and film boiling. Within section 0 fundamental properties of liquid hydrogen were reviewed, including a short section summarising thermal conductivity, thermal expansion and heat transfer coefficient research.

It is vital to understand the heat transfer properties of hydrogen under various conditions for the development of equipment handling liquid hydrogen at any scale. As such, most of the early research into the heat transfer properties was led by NASA (Merte 1970 [87], Stochl 1969 [88] and Friedman 1966 [89]) in the 1960's for understanding its viability as a rocket propellant for space missions.

While space exploration remains a key area, contemporary research also explores the use of liquid hydrogen (LH2) as a decarbonized energy vector in hard to abate sectors, as well as a cooling medium for superconducting magnets in nuclear fusion reactors. This has led to research published across various platforms like Journal of Cryogenics, International Journal of Hydrogen Energy etc.

4.2. Headlines

- Research output on the heat transfer properties of liquid hydrogen has gained significant interest in recent years, driven in part by the lack of data for flow and heat transfer information for two phase scenarios.
- Output (journal and conference papers) has nearly doubled since 2020, when compared to 2010-2020 (1032 vs 634).
- A large volume of this work comes from China and involves development of numerical models.
- Some modelling work relies on experimental data from NASA in 1960's or is validated by experimental work on other cryogenic fluids like LN2.
- Japan has reported several experimental studies, however all of them come from the same research group.
- USA has an eclectic mix of model validation reports and experimental studies. Recent publications relating to heat transfer, detail single- and two-phase studies, and include pressure drops associated with heat transfer scenarios. This includes very recent reviews of numerical models, with universal correlations proposed.

4.3. Key Research Gaps

- There is limited experimental data, often from the same sources (experimental facilities/researchers). Sub-cooled and supercritical data is limited. There is recent experimental data on flow boiling and two-phase heat transfer coefficient and universal critical heat flux. Unfortunately, not all this recent data is publicly available.

- There is a lack of aviation specific research on the effects of heat transfer (effects of vibrations, pulsed flow etc).
- There is a lack of facilities that can conduct experiments with LH2 to produce robust data.

4.4. Key Research Groups

Research Group	Country	Topic
Institute of Space and Astronautical Science, JAXA	Japan	This group have published significant amounts of experimental results with a focus on using liquid hydrogen LH2 as a cooling medium for high temperature superconductors.
Dept. of Energy Science and Technology, Kyoto University,	Japan	In collaboration with JAXA and Japan Atomic Energy Agency, nucleate and departure from nucleate boiling experimental data.
NASA Glenn Research Centre, Fluids and Cryogenics Branch, Cleveland	USA	Publications include both experimental and modelling reports with a focus on validating existing numerical models with experimental data available with NASA. Very recent publications on experimental two-phase heat transfer.
Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL), West Lafayette, IN	USA	Curation of HTC and pressure drop data for flow and nucleate boiling, generation of correlations.

4.5. Narrative

Most of the reported work in this field focuses on understanding the variation of heat transfer coefficient (HTC) and critical heat flux (CHF) of liquid hydrogen across various regimes such as natural convection, nucleate, flow and film boiling. These include stagnant and flowing states, with and without additional heat, as well as having hydrogen at a supercritical or sub-cooled state as a starting point.

The reported works can be broadly classified into five categories:

- Experimental studies in a controlled environment eliminating the effects of multiple factors on the HTC and CHF.
- Numerical and computational modelling using existing research as validation data.
- Development of artificial intelligence (AI) and machine learning algorithms to investigate correlations of various parameters on HTC and CHF.
- Validation of models by comparing the results from the numerical and Computational Fluid Dynamics (CFD) models with existing experimental data.

- Reviews of all experimental data to find correlations that can be then used to develop a robust numerical model.

Heat transfer from LH2 varies considerably depending on the velocity, pressure, orientation of flow etc. A collaboration between Kyoto University, the Japan Atomic Energy Agency and JAXA [(Shirai et al., 2021 [90], Horie (2015) [37] and Shiotsu (2015) [91]) has published several experimental papers looking into the variation of CHF and HTC by varying many of these parameters. More recently a collaboration between JAXA and Waseda University has produced experimental data and models for liquid single phase, bubbly flow, intermittent flow and initial annular two-phase flow regimes (Sakamoto et al., 2023 [48]).

In the US a collaboration between NASA and Purdue University has led to a set of detailed experimental and modelling papers. Mercado et al., (2019) [84] reviewed two phase heat transfer coefficients and critical heat flow for cryogenic flow boiling, they concluded that LH2 and liquid helium showed the worst match to used correlations. This led to the development of a flow boiling curve based on 9 test cases and the use of new universal cryogenic correlations, (Hartwig et al., 2024 [83]). Nucleate pool boiling data was separately reviewed and collated into a database by Ahmad et al., (2024) [92], with a new universal correlation proposed for seven cryogenic fluids, including LH2. Unfortunately, the dataset is confidential and not released. These correlations were integrated into the NASA developed Network solver Generalized Fluid System Simulation Program (LeClair et al., 2024 [86]), this code being available by request at https://software.nasa.gov/software/MFS-32929-1

The collaboration between Purdue University and NASA also provided universal critical heat flux correlations for cryogenic flow boiling for uniformly heated tubes (Ganesan et al., 2021 [85]).

There is literature describing the development of numerical and computational fluid dynamic (CFD) models to predict the heat transfer characteristics of LH2 using experimental data from 1960 NASA experiments (Wang 2022 [93], Fu 2022 [94] and Li 2019 [95]) or experiments on liquid nitrogen (LN2) to validate the developed models (Qiu 2023 [96], Zhang 2023 [97] and Zheng 2019 [80]). However, publications looking into validating the models were unable to identify any correlations between the experimental data and results from the various models (Baldwin 2021 [98] and Baldwin 2024 [99]). The use of machine learning has been utilised (e.g. Yang et al., 2024 [63]) to predict heat transfer coefficient based on experimental data sets.

Research on heat transfer in an aviation specific environment is fairly limited, with available research limited to development of models validated by data from ground conditions. As such the effect of aviation specific conditions like vibrations, pulsed/transient flow behaviours, impact of ‘g’ forces etc. and their effects HTC and CHF of LH2 is a key area where data is lacking.

5. Work

Work is defined here to relate to pumps, and the effects noted of liquid hydrogen on pumps. Section 14 provides information relating to pumping scenarios, whilst this section provides information specifically on cavitation and cavitation erosion that impacts LH2 pumps.

Bubble formation, via boiling, is covered within heat transfer Section 0.

5.1. Overview

Cavitation in cryogenics, particularly in liquid hydrogen, is a complex phenomenon influenced by the unique thermophysical properties of cryogenic fluids. The low boiling point and high vapour pressure of liquid hydrogen make it highly susceptible to cavitation during pressure fluctuations, such as in turbo-pumps or cryogenic transfer systems. The phenomenon poses challenges, including material erosion, reduced system efficiency, and potential flow instabilities. Understanding cavitation in liquid hydrogen is critical for designing reliable cryogenic systems.

Despite its significance in critical applications such as space pumps, research in this area is limited, with much of the foundational work dating back to the 1970s.

The development of advanced cavitation models that couple thermal and inertial effects presents a significant opportunity for advancing the understanding of cryogenic cavitation. These models would offer better predictions of bubble dynamics and cavitation behaviour in liquid hydrogen systems, addressing many of the current limitations.

5.2. Key Research Gaps

- Limited experimental data is available for cavitation in liquid hydrogen, with most from NASA in 1970s.
- Ito (2021) [100] describes a facility for cryogenic cavitation on impellers, but there are no subsequent papers and no presence on the web.
- Lack of experimental validation limits the refinement of numerical models, making it difficult to predict cavitation behaviour accurately. Many existing models do not fully account for the thermal interactions that significantly impact bubble dynamics at low temperatures.
- Fundamental research on bubble collapse dynamics and low-temperature experiments is notably absent in the context of cryogenics, further hindering the development of robust and reliable cavitation models.
- Some research has shown that cavitation is less of an issue for cryogenic liquids (Nitrogen) compared to water. Research following on from NASA 1970's publications have been predominantly numerical/computational and sought to capture the complex thermofluids behaviour, including thermodynamic suppression head, that impacts cavitation in cryogenic fluids.
- Modern experimental facilities are urgently needed to provide key data to enable understanding of pump behaviour in cryogenic hydrogen storage and fuel system.

5.3. Key Research Groups

Institution	Country	Topic
Institute of Refrigeration and Cryogenics, Zhejiang University Zhu et al., (2016) [101] , Yuan et al., (2022) [102]	China	Modelling using Hord et al., (1972) [103] and (1973) [103] [104] for validation.
School of Energy and Power Engineering, Xi'an Jiaotong University Sun et al., (2021) [105]	China	Commercial RANS CFD code used for modelling tool, using Hord et al. (as above) for validation.
Department of Aeronautics and Astronautics, The University of Tokyo, Ito (2021) [100]	Japan	Detailed description of facility, although liquid hydrogen is mentioned there are no published results or visualisations.

5.4. Narrative

Liquid hydrogen exhibits heightened sensitivity to its thermophysical properties, necessitating further research to refine the phase diagram under varying pressure and temperature conditions. Vapor pressure is especially critical in cavitation modelling, and its accurate characterisation is essential for reliable simulations. Experimental studies in cryogenic cavitation are scarce, with most available data originating from NASA's efforts in the 1970s (Hord et al.,1972, 1973 [103], [104]). The lack of experimental validation limits the refinement of numerical models, making it difficult to accurately predict cavitation behaviour.

It is vital that thermodynamic effects are incorporated in cavitation models to accurately simulate cryogenic conditions. However, many existing models do not fully account for the thermal interactions that significantly impact bubble dynamics at low temperatures. Several models, such as the Rayleigh-Plesset, Zwart-Gerber-Belamri, and Schnerr-Sauer models, have been developed to incorporate thermodynamic effects (Hosangadi et al., 2010 [106]., Kelly et al., 2011 [107]., Huang et al,. 2002 [108], Zhang et al,. 2018 [109]) . These studies require further adaptation to reflect the unique characteristics of cryogenic fluids like LH2. Fundamental research on bubble collapse dynamics and low-temperature experiments is notably absent in the context of cryogenics, further hindering the development of robust and reliable cavitation models.

Research on cavitation erosion at cryogenic temperatures is similarly limited. An experimental study using liquid nitrogen (Dular et al. [110]) was found in the literature which showed that erosion in cryogenic fluids is less severe than in water, primarily due to increased material hardness and reduced erosion intensity at low temperatures. This reduced impact, coupled with the fact that cryogenic systems like those in rocket propulsion are typically single-use, has led to limited research interest in this area. As a result, the broader implications of cavitation erosion in cryogenics remain largely unexplored.

6. Magnetic

6.1. Overview

Hydrogen exhibits different magnetic properties depending on its form. Atomic hydrogen is paramagnetic due to its unpaired electron, making it weakly attracted to magnetic fields. In contrast, molecular hydrogen is diamagnetic, it is affected by magnetic field because the bonds between hydrogen atoms and between hydrogen and other elements are (usually) due to magnetic interactions. As for the two states ortho- and para-; ortho-hydrogen (which has parallel nuclear spins) is weakly paramagnetic, whereas para-hydrogen (which has antiparallel spins) is diamagnetic. At cryogenic temperatures, para-hydrogen is the more stable form. If sensors utilising magnetic fields or electrical fields are to be used within cryogenic hydrogen storage and fuel system better characterisation is required, particularly the impact on ortho-para conversion or properties.

Research on the magnetism of hydrogen covers a wide range of subtopics, resulting in recommended papers that provide quite specific insights rather than a comprehensive general review. These include papers by Cwik et al. (2024) [111], Feng et al. (2020) [112], van der Minne et al. (2024) [113] and Snadin et al. (2024) [114].

The use of LH2 to cool the windings of electrical machines or electromagnetics, sometimes referred to as cryomagnetics is outside the scope of this review. Likewise, the use of magnetism to boost hydrogen production or within liquefaction is outside the scope of this review.

6.2. Key Research Gaps

- No dedicated research has been found specifically investigating the direct effects of magnetic fields on LH2.
- Limited research on modelling impact of magnetic fields on LH2, with ID models using commercial software dominate.

Research on the effects of magnetic fields on hydrogen has been conducted over the past century, largely at the molecular level and typically not at cryogenic temperatures. More recent studies have explored applications such as magnetic refrigeration for hydrogen liquefaction, magnetic levitation to reduce losses in LH2 storage, and the influence of magnetic fields on catalysts used in hydrogen production. However, no dedicated research has been found specifically investigating the direct effects of magnetic fields on LH2, aside from occasional mentions in forums and informal discussions. This highlights a significant research gap in understanding the impact of magnetic fields on LH2 at cryogenic temperatures.

Most of the research in this scope is experimental. Only two papers had mathematical (1D) modelling. Only one numerical calculations was found on magnetism related to LH2, which used Comsol and Paradiso, and thermal quantities are studied and validated against experiments from past literature.

6.3. Key Research Groups

Most of research (30% of the papers in the scope) of magnetism related to LH2 is covered by Japan, largely experimentally. USA and Germany performed much research on this topic (17% of the scope each). Poland, Switzerland, Russia and Netherlands also showed interest in this topic.

Institution	Country	Topic
Kyoto University Hara et al, (2021) [115], Shirai et al, (2016) [116]	Japan	Use of Liquid Hydrogen for cooling relating to superconducting generators.
NHMFL, National High Magnetic Field Laboratory, FSU Tallahassee, Florida, Charignon et al., (2008) [67]	USA	Focus on heat transfer research.
High Energy Research Accelerator Organization, Tsukuba (Hirabayashi et al., 2006; 2008 [117, 118])	Japan	Advances fundamental science focussing on particle physics, nuclear physics and materials science.
National Institute for Materials Science, Tsukuba (Matsumoto et al., 2009 [119]; Tang et al., 2022 [120])	Japan	Study magnetic refrigeration during hydrogen liquefaction.

6.4. Narrative

The main research on hydrogen impacted by a magnetic field involves the ortho-para conversion, which is also covered in Section 0. For instance, Snadin et al. (2024) [114] is a useful paper to see the dependence of ortho-para conversion in a wide range of magnetic fields (in the presence of a catalyst), which includes experiments, numerical calculations and analysis.

Apart from the ortho-para hydrogen conversion in magnetic field, two main types of LH2 research related to magnetism exist. One is where LH2 is used for a coolant, the second is when magnetism is used to improve efficiency in LH2 technologies, such as using magnetic bearings and levitation or efficiency improvement for catalysts used for hydrogen production.

Hara et al., (2021) [115] is an example of the use of LH2 for cooling of superconducting generators and highlights the collaboration between Kyoto University with the Japan Atomic Energy Agency and Japan Aerospace Exploration Agency.

Large amount of research on magnetic effects on LH2 is very recent, demonstrating rapid advancements and interest in magnetic effects to improve LH2 technologies.

Main topics:

- Magnetic refrigeration for potential use in hydrogen liquefaction (useful review by Zhang et al., 2019 [121]): Magnetic refrigerators utilise the magnetocaloric effect; they emerge as a promising alternative to conventional gas-compression refrigeration due to its environmental friendliness and high energy efficiency. This innovative technology is effective at low temperatures, making it suitable for potential use in hydrogen liquefaction. Liquefaction at airports links with the refuelling scenario described in section 0.
- Contactless superconducting suspension for reduction of LH2 storage losses, Walter et al., (2003) [122]: used to minimise heat transfer to the inner tank of a hydrogen storage system. In conventional designs, the inner tank is physically connected to the outer tank via fixed supports, which act as thermal bridges, allowing heat to flow into the inner tank. By using a superconducting suspension, the inner tank is levitated without physical contact, eliminating direct thermal conduction through support structures. Minimisation of heat ingress for on-aircraft LH2 storage is a key area for mid-TRL development.
- Catalysts performance improvements for hydrogen production (van der Minne et al., 2024 [113]): researchers discovered that controlling the magnetic "spins" of atoms in the catalyst during the reaction significantly accelerated the process. Additionally, they found that applying an external magnetic field further enhanced the catalyst’s performance, making the reaction even more efficient. This study explores fundamental scientific principles.

7. Acoustics

7.1. Overview

Low TRL research into the impact of acoustics on the thermofluid behaviour of Liquid Hydrogen (LH2) is reviewed within this section.

The motion of acoustic waves through moving and stationary flow is well known. M. J. Lighthill's series of papers through the 1950's – 1960's providing the basis for sound generation and propagation aerodynamically (Lighthill 1952 [123], Lighthill 1962 [124]). The book, Engineering Acoustics by Fahy, (2000) [125], provides a general text to describe the propagation of sound through fluids. A fluid's pressure, temperature, density and compressibility all impact the propagation of acoustic waves and close to a surface viscosity is important. Where a liquid has gas bubbles within the fluid, this has a significant effect on the speed of sound, attenuating and scattering sound waves.

Thermoacoustics is the study of both acoustics and thermodynamics, and the transference of energy. It can also be defined as the interaction of temperature, density and pressure variations of acoustic waves. For a fuller understanding of thermoacoustics, the book by Swift, (2017) [126] is recommended.

Thermoacoustic instabilities within combustors is a well-researched area and is outside of the scope of this review. The book of combustion instabilities by Lieuwen and Yang, (2005) [127] provides a reference if this area is of interest.

Thermoacoustics links to both heat transfer and work aspects of liquid hydrogen and the narrative section, 7.4, describes recent low TRL research in this area. As thermoacoustics is linked to the fundamental properties of the fluid, Section 0 is relevant to understand the robustness of data in density, for example.

For aviation, acoustics or thermoacoustics, are of significance in relation to the behaviour of the fluid around key pressure point changes, for instance, during valve closing or chilldown. The potential interactions between airframe vibrations and the transference of this vibration to fluid borne acoustics is also of concern, given the impact this may have on heat transfer and phase control. This may also have an impact on sensor accuracy.

7.2. Key Research Gaps

- Only one paper was found to investigate LH2 fluid hammer effects via modelling, with very limited experimental data available to validate this.
- There is only one research institute visible that is investigating Taconis oscillations experimentally (Hyper Lab Washington State University). Given that Taconis oscillations impact heat flux and can impact instrumentation (vibration), these data sets are of key importance.
- Data on the impact airframe vibrations transference to thermoacoustics was not found within the published literature.
- Modelling is predominantly 1D thermoacoustic or uses Method of Characteristics, with only a small number of institutions active in researching in this area.

7.3. Key Research Groups

Institution	Country	Topic
CAS Key Laboratory of Cryogenic, Chinese Academy of Sciences, Beijing	China	Thermoacoustic refrigeration studies.
Liquid Propulsion Systems Centre, Indian Space Research Organisation, Thiruvananthapuram, Kerala, Joesph et al., (2017) [128]	India	Single paper on LH2 fluid hammer.
Hydrogen Properties for Energy Research (HYPER) Center, School of Mechanical and Materials Engineering, Washington State University	USA	Mixture of modelling (1D thermoacoustics) and experimental data capture applied to both Taconis and thermoacoustic refrigeration.

7.4. Narrative

There are instances where thermoacoustic effects on LH2 increase heat leakage, as well as impacting instrumentation, due to Taconis oscillations (Shenton et al., 2024 [129] [130] , Sun et al., 2016 [131]). Taconis oscillations were first reported in 1949 relating to helium (Taconis et al., 1949 [132]) where oscillations were identified within piping with an open end within the dewar in the cryogenic fluid and a closed end outside of the dewar. Shenton et al., (2024) [129, 130], reviews past literature on Taconis oscillations within Table 1 in the paper, providing a succinct summary of papers relating to LH2 from 1967 to 2024. The research in this area remains at low TRL with limited experimental data available to validate modelling work.

A separate phenomenon, fluid hammer, is the term used for pressure oscillations in pipe flows typically caused when a valve closes. In addition, this phenomenon can occur for cryogenic systems if pipework is insufficiently insulated, causing evaporation to occur, triggering a pressure surge (Joseph et al., 2017 [128]). A method of Characteristics (MOC) model was utilised by the Indian Space Research Organisation (Joseph et al., 2017 [128]) to simulate the situation where a chill down valve was closed in a liquid hydrogen feedline triggering pressure oscillations.

Research has also investigated how to harness the thermoacoustic effects for LH2, either for cryocoolers (Matveev & Leachman, 2022 [133]), for a heat-driven thermoacoustic refrigerator (Matveev & Leachman, 2024 [134]) or a gas–liquid-coupled thermoacoustic refrigerator (Chi et al., 2021 [135]). The impact of thermal acoustic oscillations in cryogenic systems is described with examples in Putselyk, (2020) [136].

There are publications from Gu & Timmerhaus (Gu et al., 1992 [137]) that investigate the damping criteria of thermoacoustic oscillations in slush and liquid hydrogen systems by analysing investigations on stability criteria, referencing NASA contractor reports. The impact of tube radius, length ratio of warm to cold section and varying the temperature ratio or profile along the tube were considered in investigations. However, there appears to be no research in this area after this date. There were no publications found reviewing the link between mechanical or airborne vibration impacts onto thermoacoustic phenomena within liquid hydrogen.

8. Electrical

8.1. Overview

This section reviews available literature on the impact on LH2 of electrical fields. The available research can be classified into two areas. The first area investigates flow electrification characteristics of LH2 in pipes (Bowen et al., 2023 [138], Liu et al., 2024 [139] and Liu et al., 2023 [140]), while the second area studies the effect of electric field on the liquid-vapour surface of charged LH2 (Abdurahimov et al., 2012 [141] and Brazhnikov et al., 2001 [142]) also called Electrohydrodynamic (EHD), of LH2.

While there is considerable research on using LH2 as a cooling medium for achieving superconductivity, research on the impact of electric fields on LH2 is limited due to the intrinsic properties of LH2 (low dielectric constant, discussed in section 3.4.6), low electric conductivity, non-polar nature etc).

Flow electrification characteristics of LH2 in pipes has significant impact on aerospace applications, with the friction at the solid-liquid interface potentially developing static charges, which can accumulate in LH2. This phenomenon, if left unchecked, could lead to an ignition hazard from electrostatic discharge, which is reviewed within the Cryogenic Hydrogen Health and Safety Global Research Landscape report. While flow electrification in oil and other fuels is a well-researched topic, there is very limited research on flow electrification for LH2. Most of the available research uses numerical modelling to predict flow electrification, with the models validated using the experimental data from proxy fluids like oils. This approach lacks robustness.

Contrary to flow electrification research, most available research studying the effect of electric field on the surface of charged LH2 are experimental and studies how an electric field deforms the liquid-vapour surfaces developing waves or even small jets under strong fields. While the research could have applications for managing LH2 on-board aircraft (such as to counteract external forces) this never has been the focus of the published research (Abdurahimov et al., 2012 [141], Brazhnikov et al., 2001 [142], Kolmakov et al., 2002 [143] and Abdurakhimov et al., 2012 [144]).

8.2. Key Research Gaps

- Lack of experimental data for accurate model development in flow electrification of LH2 that accounts for various effects like vaporisation, impurities etc.
- Lack of research looking into the application of an electric field on the liquid-vapour surface (EHD) of charged LH2 in aircraft situations.

8.3. Key Research Groups

Research Group	Country	Topic
Institute of Refrigeration and Cryogenic Engineering, Xi'an Jiatong University	China	The research group focuses on flow electrification of LH2 flowing through pipes.
Institute of Solid State Physics, Moscow	Russia	The research group experimentally studies the interaction of electric fields on charged LH2 surfaces.

8.4. Narrative

As mentioned in the overview section, the research on the effect of electric fields on LH2 is very limited.

All the work involved in flow electrification was carried out by a single group in China and involved developing models to predict the effects of flow parameters on the flow electrification of LH2. The group further expanded the model to account for electrostatic saturation that could occur when LH2 is transported over longer distances in pipes (>10m). However, these models were validated using experimental data from transporting hydrocarbons. As a result, the models' capabilities are limited to few parameters, like pipe radius, flow velocity etc. The model is unable to capture effects of impurities, gas bubbles from phase change, turbulence in cryogenic conditions etc., all of which require robust experimental data which is not available at time of writing this report (Bowen et al., 2023 [138], [140] Liu et al., 2024 [139] and Liu et al., 2023 [140]).

The available research on EHD of LH2, is carried out mainly by a single research group based in Russia. Most of their work is experimental and analyses the effect of electric fields produced by AC and DC currents on the charged surface of LH2. These studies investigate how electric fields can induce instabilities on the surface of LH2 under charged conditions, as well as the development of wave structures and Taylor cones under strong electric fields (Abdurahimov et al., 2012 [141], Brazhnikov et al., 2001 [142], Kolmakov et al., 2002 [143] and Abdurakhimov et al., 2012 [144]). Their experiments show that hydrodynamic behaviour of LH2 can be controlled or altered by using electric fields.

9. Contamination and Fluid Mixtures

9.1. Overview

This section reviews low TRL research for liquid hydrogen with contamination and where there is a fluid mixture of liquid hydrogen and helium. The contamination of liquid helium by solid hydrogen is not covered in this review, a recent publication by Will & Haberstroh, (2020) [145] is recommended for those interested in this area.

It should be noted that the literature typically discusses binary mixtures for fundamental flow information, with % mole fractions, rather than regarding this as contamination of liquid hydrogen.

There are two main areas of low TRL research that can be identified from the literature:

- Studies of helium injection into liquid hydrogen tanks for pressurisation.
- Fundamental studies of the properties of liquid hydrogen with different trace fluids/solids.

9.2. Key Research Gaps

- There is no experimental data on the growth of solid air within liquid hydrogen available within the literature.
- There is limited research on the impact of helium solubility on liquid hydrogen properties.
- There is limited research on the impact of binary mixtures on liquid hydrogen properties.

9.3. Key Research Groups

Research Group	Country	Topic
State Key Laboratory of Technologies in Space Cryogenic Propellants, (Zheng et al., 2023 [146])	China	Numerical investigation of solid-air particles within liquid hydrogen.
Department of Energy and Process Engineering, Norwegian University of Science and Technology, in collaboration with SINTEF Energy Research, Trondheim (Hammer et al., 2023 [147])	Norway	Equations of state for mixtures of helium, neon, hydrogen and deuterium.

Research Group	Country	Topic
Saint Petersburg State University of Architecture and Civil Engineering in collaboration with Peter the Great Saint Petersburg Polytechnic University, (Boryaev et al., 2022 [81])	Russia	Liquid helium and hydrogen use and impact during fill and drain of storage tanks.
Hyper Lab, Washington State University (Richardson & Leachman 2017) [148] Cavender et al., 2017 [149])	USA	Assessment of Thermofluids properties, including for binary mixtures and for dissolved helium.

9.4. Narrative

Lozano-Martin et al., (2022) [150] has reviewed experimental data and thermodynamic models for pure hydrogen and mixtures. This review focused on vapour-liquid equilibrium, density, speed of sound and other caloric properties of hydrogen and mixtures, predominantly relating to gaseous hydrogen. There is very limited reference to cryogenic mixtures, with works from HYPER lab at Washington State University referenced.

The vapour-liquid equilibria of neon, helium, hydrogen and deuterium has been studied recently due to the increasing interest in liquefaction of hydrogen. The potential for these fluids to be present in liquid hydrogen is due to their use as refrigerants in the liquefaction process. At temperatures ~20K quantum effects can significantly impact surface tension, and other interfacial properties (Hammer). Hammer et al., (2023) [147], created a model to account for the presence of fluid mixtures on the value of surface tension based on experimental data from the 1960-1990's. The model builds from a classical density functional theory for Feynman-Hibbs-corrected Nie potentials.

Starvin et al., (2021) [151] utilised a tanker of 20m^3 to experimentally study subcooling of liquid hydrogen by evacuation and compares this to predictions of the use of gaseous helium to provide sub-cooling. Boryaev et al., (2022) [81], reviews the use of liquid helium within a cryogenic hydrogen storage and fuel system. They provide both data and correlations for helium solubility into liquid hydrogen as a function of temperature and partial pressure.

Liang et al., (2021) [152], modelled erosion of solid air particles in liquid hydrogen but validated this against data from hydrocarbon scenarios due to the lack of experimental data for solid-air particles in liquid hydrogen. There are a number of papers (e.g. Zheng et al., 2023 [146]) that have numerically investigated the growth of solid-air particles in liquid hydrogen using a range of different numerical approaches, however there is no experimental data provided with these papers.

10. Surface and Material Interactions

10.1. Overview

Different material surfaces interact very differently with liquid hydrogen, due to variations in properties such as wettability (dynamic contact angle), adsorption, thermal conductivity, and magnetic behaviour. This section provides an overview, whilst the Cryogenic Materials Global Landscape Research Landscape report will provide additional context.

These interactions can significantly affect the efficiency, safety, and performance of hydrogen storage and transport systems. The specific material chosen for these applications may also play a crucial role in minimizing hydrogen losses, enhancing system performance, and reducing material degradation.

10.2. Key Research Gaps

Properties such as roughness, wettability, adsorption, permeability, thermal conductivity and magnetic influence impact hydrogen flow behaviour (e.g., mass transfer, turbulence structures, heat transfer of both, gaseous and liquid hydrogen flows). Ongoing research is investigating coatings impact on the hydrogen flow behaviour and embrittlement resistance, occasionally addressing their effects at cryogenic temperatures or high pressures (Patil & Doddagoudar, 2019 [153]; Hauer et al., 2024 [154]). For example, porous materials can adsorb hydrogen, causing loss or contamination; metals are susceptible to embrittlement; high thermal conductivity increases boil-off, while low conductivity minimizes it; and ferromagnetic materials can alter hydrogen flow through magnetic field generation. Given these established effects on gaseous hydrogen, it is highly likely that similar interactions occur with liquid hydrogen. However, research in this area remains limited, representing a significant gap in current knowledge.

- There is a lack of fundamental research on the interaction of LH2 with materials across the conditions found in a LH2 system. Important effects for thermofluids include wettability, adsorption, permeability, thermal conductivity, and magnetic influence.
- Whilst coatings may provide an effective approach for controlling surface/fluid interaction there are research gaps in knowledge of coating interactions, production methods, material behaviour, temperature resilience, and commercial viability.

10.3. Key Research Groups

Influence of the surface on LH2 properties/behaviour is studied almost entirely experimentally. Such properties as wettability, surface roughness, surface coatings and porosity and their influence on LH2 directly or LH2 storage efficiency are included in this scope.

Interest on how variation of the solid surface may influence LH2 and LH2 storage materials, has rapidly increased in the last decade. Researchers are exploring methods to potentially improve safety and increase the life span of LH2 storage.

Institution	Country	Topic
Fraunhofer Institute for Large Structures	Germany	Surface coating plus steel-fibre composite.
University of Rostock	Germany	Surface coating plus steel-fibre composite.
Kyushu University, partner in HYDROGENIUS	Japan	Surface coatings.
Massachusetts Institute of Technology	USA	Surface roughness.

10.4. Narrative

Wettability is defined as the preference of a liquid to be in contact with a solid surrounded by another fluid, either liquid or gas. Wettability is determined by the three materials – solid and two fluids, with the contact angle a principal factor in the interaction between materials and liquid hydrogen. Materials can either be hydrophilic (wettable) or hydrophobic (non-wettable). Metals generally exhibit good wettability with LH2 (Good & Ferry, 1963 [155]). In contrast, non-metallic materials like certain polymers or coated surfaces may have poor wettability, which would lead to liquid hydrogen film breakup or droplet formation, complicating storage, and flow control. However, contact angles and wettability of LH2 with plastic and various coatings is limited. Wettability, and a directly related property surface tension, were studied in the 1960s-90s, although there is little recent research.

Surface coatings help maintain the integrity of storage tanks and other equipment, extending their service life and improving safety. Superhydrophobic coatings could significantly reduce LH2 adhesion to surfaces. Lei et al. (2022) [156] performed mathematical modelling of unsteady-state hydrogen diffusion through coated steel, to assess the impact of a PVA coating on hydrogen concentrations within the steel. The results show that a 1mm coating can extend the hydrogen concentration on the steel surface. However, the effect of these concentration changes on hydrogen embrittlement remains unclear due to insufficient literature on the threshold concentration causing this issue.

Hauer et al. (2024) [154] suggested a novel tank design approach by using two advanced technologies from space and high-temperature applications, and addressing strict requirements for transport weight, insulation, and cryogenic durability. The first involves fibre-reinforced plastic–steel hybrid tanks, which offer significant potential for LH2 storage, but are currently used only in the space sector. Challenges remain regarding coating interactions, production methods, material behaviour, temperature resilience, and commercial viability. The second focuses on thermally sprayed thermal barrier coatings, which provide protection against extreme thermal and mechanical stress. While currently limited to high-temperature applications, these coatings require adaptation for use in cryogenic environments, expanding their potential for hydrogen storage and transport.

11. Fluid Monitoring, Sensing and Control

11.1. Overview

This section covers research in and methods on how to measure LH2 properties and ensure that measurements can be undertaken in experimental design. Key considerations include methodology and uncertainty quantifications. Much of the fundamental experimental data collected on LH2 dates back to the mid-twentieth century; the key research gaps in this section highlight the areas in which there is either little update in experimental measurement techniques since this time or where experimental techniques are not available. This section does not cover sensing for mid-TRL research or industrial processes; for example, flow meters and capacitance sensors for LH2 pumping or fuelling systems are out of scope.

Some of the original experimental setups included:

- Modified cryostats with insulated cylinders for thermal conductivity measurements (Dwyer, 1966 [157] and Charignon, 2008 [67]) or applied pressure gradients for vapour pressure measurements (Hoge, 1951 [33]).
- Torsional oscillator for viscosity measurements (Webeler, 1961 [34]).
- Capacitance to measure density (Snyder, 1969 [55]).
  - Note: capacitance measurements rely on a knowledge of the dielectric constant of the fluid (Corruccini,1962 [74]). Multiple modern publications cover capacitance for level sensing (Behruzi, 2023 [158]).

These fundamental experimental techniques are still suitable for measuring LH2 properties, and information on new experimental techniques for these measurements has not been found. No information has been found on new experimental techniques used to measure fundamental properties. It is unclear if this lack of new sensor technology (or new experimental techniques) is due to insufficient demand or if the existing technology remains suitable. However, there is a gap in exploiting and developing new sensing and experimental techniques for fundamental liquid hydrogen thermofluid properties.

More recent experimental techniques include:

- Neutron scattering to identify ortho- and para-hydrogen fractions (Barron-Palos, 2011 [159] and Grammer, 2015 [160]), vapour-liquid interfaces (Bellur 2022 [42]), or to investigate the microscope structure of LH2.
- Gamma ray densitometry to determine density or fractions in two phase mixtures.
- Optical techniques, particularly for multiphase flow. Frequently high-precision and high-speed cameras are suitable for both quantitative and qualitative measurements (examples include Xie, 2023 [161] and Sakamoto, 2021 [162]).
- Radio and/or acoustic waves for level and volume sensing (Nakano, 2016 [163] and Filippov, 2023 [164]).
- Quantum state measurements of hydrogen such as those detailed in section 0.

11.2. Key Research Gaps

Areas in which little information on LH2 experimental setup has been found include:

- Transient behaviour quantification, such as understanding multi-phase flow like that which may be seen in a pipe or pumped system.
- Optical techniques to link with transient behaviour, boiling, and multiphase flow.
- Further investigation into novel radio frequency or wider acoustic techniques.
- Sloshing measurement and characterisation, which links with transient behaviour quantification.

Areas in which further development could be beneficial include:

- Use of modern sensing equipment with improved accuracy and repeatability to minimise uncertainty in fundamental LH2 properties.
- Application of methods used for other cryogenic fluids to LH2.
- Use of optics coupled with AI or neural networks to support understanding of multiphase flow, including sloshing.

NASA research on fundamental properties shows that fundamental LH2 properties can be measured using existing sensing and experimental technologies, although there is a gap in understanding of how more modern sensing techniques could minimise uncertainty in existing data. Uncertainty around phase change and the triple point is particularly vital for modelling and prediction.

Accurate data of phase changes is vital for understanding and modelling of two-phase flow. However, given that there are multiple external factors which influence two-phase flow, experiments which allow for accurate quantitative data to be gathered are vital. More modern experimental techniques which can capture transient behaviour, such as acoustics and optics, need to be investigated to allow this data to be taken.

11.3. Key Research Groups

This table highlights important research groups currently working on LH2 experiments with modern techniques (*i.e.* have papers published from 2015 onwards). It does not cover research groups which are no longer active, and it does not include those that either have non-unique methodologies (such as using cameras or standard fluid measurement apparatuses) or have single publications on a topic.

It is recommended that this table is linked with those shown in sections 0 through 0.

Institution/Company	**Country**	**Topic**
HYPER Laboratory, Washington State (Pullman)	USA	Experimental devices for LH2 fundamental properties.
JAXA	Japan	Experimental setups for LH2 heat transfer and boiling.

Institution/Company	Country	Topic
Los Alamos National Laboratories (NM) and Oak Ridge National Lab (TN)	USA	Experimental work on Ortho-Para fractions in LH2 using cold neutron capture.

11.4. Narrative

Accurate, reliable, and accessible sensing equipment and experimental setups are required to gather LH2 data which can be used in models, software, and scenarios. Many of the references considered in this section link with those found in the rest of this report. This section links across all sections which have investigated experimental data. It also links with the sister report Cryogenic Hydrogen Health and Safety Global Research Landscape in experimental work for measuring leakage, dispersion, and ignition.

Experimental research primarily led in the United States and others (examples include Chi, 1964 [165], Corruccini, 1962 [166] , Hoge, 1951 [33], Snyder, 1969 [55]) in the mid-twentieth century on fundamental LH2 properties show that experimental apparatuses were suitable to obtain data, but the scatter and understanding the data uncertainty from these datasets is mixed (Leachman, 2007 [22]). In some cases, the existing techniques are being applied to more complex phenomena such as heat transfer and boiling (Shirai 2021 [90]). More modern techniques for measurements could be applied to understanding LH2 fundamental properties to refine and expand the original data, including through minimising uncertainties. However, no evidence has been found to indicate that development in fluid monitoring and sensing is required to enable this research to occur, i.e. no phenomena has been immeasurable due to lack of instrumentation and sensing.

Optical techniques can be used to quantify and understand multiphase and/or transient systems. Twenty first century experimental papers frequently use cameras to give both qualitative and quantitative information. For example, Xie et al. (2023) [161] used a camera to study the freezing and thawing processes of slush hydrogen and Sakamoto (2021) [162] used a high-speed camera to investigate boiling. Videos are also vital for understanding health and safety experimental work, such as that undertaken by the HSE in the UK. Modern processing techniques (such as AI or neural network training) can assist in processing large amounts of information.

More novel techniques which could be investigated include the use of radio or acoustic waves for volume and level, and therefore density, measurements. Neutron imaging is being used to measure fundamental properties of hydrogen such as vapour liquid interfaces (Bullar et al. 2022 [42]), ortho-para conversion, and quantum dynamics. The use of such techniques at a laboratory scale can allow for verification in industrial process. Indeed, fluid monitoring and experimental sensing links closely with higher TRL work on systems and sensing equipment. Work on LH2 specific sensors for level measurement links with capacitance measurement and the relative dielectric constant of LH2 and GH2. Flow measurement, particularly two-phase flow measurement, relies on knowledge and sensing of vapour and liquid quantities.

12. Experiment Design - Proxy Fluids / Scaling

12.1. Overview

This section reviews the approach to using alternative fluids, typically known as proxy fluids, to obtain experimental data that can then be used to validate thermofluid behaviour within systems. These proxy fluids are used in place of LH2 for reasons such as safety, cost, and availability.

Common proxy fluids include Liquid Nitrogen (LN2), Liquid Helium (LHe), Liquid Oxygen (LO2), and water. Experiments with these fluids are often used to validate numerical and computational models, which are then used to simulate the same scenario but with LH2 as the working fluid. The differences in fundamental fluid properties (such as those discussed in section 0) may be mitigated by using non-dimensional quantities.

This approach of using similarity arguments enables researchers to investigate effects of various parameters on heat transfer, spills and leakages, as well flow dynamics of LH2, while circumventing the complications associated with building facilities that can safely handle LH2.

Among the proxy fluids, LHe is preferred for experiments looking into leakages and spills of LH2 (Li 2018 [167], Soleimani 2019 [168], Shu et al., 2022 [169], He et al., 2024 [170]) while LN2 (Nishizu, 2006 [171] and Nakano et al., 2006 [172]) is often used to carry out experiments associated with heat transfer. Water is used to understand fluid dynamics of LH2, such as sloshing (Liu et al., 2019 [173] and Wei 2020 [174]).

With suitable experimental evidence to support their use, proxy fluids can enable more complex phenomena to be studied and understood more rapidly. However, there are limitations to the situations in which proxy fluids are suitable. One example is in the certification and confirmation of airworthiness of components; the design may be aided or guided by such development, but proxy fluids would not be able to replace LH2 testing in these scenarios.

12.2. Key Research Gaps

- Lack of experimental data to verify similarity assumptions or develop correlations between proxy fluids and LH2.

12.3. Key Research Groups

Research Group	Country	Topic
Department of Mechanical Engineering and Institute for Integrated Energy Systems, University of Victoria	Canada	The research group have conducted experiments using Helium as a proxy fluid to learn about the behaviour of hydrogen leakages from cracks in pipelines, tanks etc.

Research Group	Country	Topic
State Key Laboratory of Technologies in Space Cryogenic Propellants, Beijing	China	The group used liquid helium to understand the spill behaviour of LH2.
CEA Saclay, DEN/DANS/DM2S/SFME/Laboratoire d'Etudes Expérimentales des Fluides, 91191 Gif-sur-Yvette	France	Research using gaseous helium to determine the behaviour of hydrogen leaks in enclosed spaces like garage.
National Institute of Advanced Industrial Science and Technology (AIST), 1-2-1 Namiki, Tsukuba East, Tsukuba	Japan	The research group used liquid nitrogen to development volume measurement methods for measuring LH2 under microgravity.

12.4. Narrative

In many cases where proxy fluids are used, such as in the case of He et al. (2024) [170], analysis linking the proxy fluid to how LH2 may behave is not shown in the publication. In some others, such as Shu et al. (2022) and Li et al. (2018) [167], comparisons are made to historical experimental data gathered in approximately the same method. Separately, some work on heat transfer uses two different fluids (LN2 and LH2) in the same experimental setup (Shirai et al., 2016 [116]). In the latter work, a general correlation for heat flux was proposed.

The differences in fundamental properties between regularly used cryogenic fluids (LH2, LH2, LO2, LHe, and liquid methane) is clearly shown by Hartwig (2016) [176, 177]. Compared to LN2 and LO2, the density and surface tension of LH2 is an order of magnitude smaller. Whilst non-dimensional numbers and correlation factors can allow for similarity arguments to be developed, these need to be tested and validated.

There is a body of research using proxy fluids published from around the world with China having a large volume of publications with this approach. The experiments conducted are often used to validate numerical or computational models which is in turn is used to simulate the effect if the working fluid in the experiments were LH2. The use of proxy fluids could be a safe and cost-effective way to study various aspects of LH2, but the effectiveness of the use of proxy fluids needs to be demonstrated.

The papers which have been found to use proxy fluids instead of LH2 investigate complex phenomena or scenarios. These frequently focus on transient systems in which multiple fundamental properties are dynamically changing concurrently (such as, for example, density and temperature). When LH2 data is available, either through concurrent experiments or historical ones, the suitability of the proxy fluid and any associated similarity or correlation arguments can be assessed for that particular set of conditions. These correlations or mathematical links have not been proved to be applicable in other conditions. In order to develop a dataset and improve confidence in the use of proxy fluids as a replacement for LH2 in experiments and modelling, a suite of controlled and concurrent experiments needs to be undertaken to build up the knowledge base. This will likely require a targeted approach to ensure the suitability of the proxy fluid for the correct design/application. Such work would be beneficial in supporting inherently safer and cost-effective research on LH2.

13. Modelling Techniques (Multiphysics/Scale/Fidelity)

13.1. Overview

This section overviews the modelling approaches available for simulating LH2.

Numerical modelling of thermofluids phenomena in liquid hydrogen (LH2) is essential for understanding its behaviour under cryogenic conditions and optimising its use in aerospace, energy, and transportation systems. LH2's unique thermophysical properties, including its low boiling point and high vapor pressure, require specialised models to simulate key processes accurately.

There are four types of modelling approaches currently employed to investigate LH2 thermofluids behaviour which are listed below and are described further, including current research, within the narrative section 13.4.

- High fidelity numerical modelling tools, i.e. direct numerical simulations (DNS), large eddy simulations (LES).
- Reynolds Averaged Navier Stokes Computational Fluid Dynamics (RANS CFD).
- Bespoke modelling tools.
- Low Order, 1D/System modelling tools.

It is worth noting that the validation for all of these approaches is limited due to the lack of available experimental data. There are also uncertainties associated with the assumption of pure fluid in the equations of state: Leachman et al., (2009) [7] stated an uncertainty in density of 0.2% for saturated liquid hydrogen, 0.1% from triple point to 250K and for pressures up to 40MPA, rising to 0.2% in the critical region. Uncertainty for heat capacities are stated as 1% whilst vapour pressures 0.2%. Acceptable levels of uncertainty are dependent on the application and the modelling techniques used.

All of the tools require detailed understanding of the physical situation, including boundary conditions, as well as an understanding of the sub-model's appropriateness and choice of terms/coefficients. This means that specialist knowledge of the tool, cryogenic behaviour and hydrogen behaviour are required to ensure a robust analysis. There are some models, for example evaporation/boil-off sub-models, which require the use of a parameter/coefficient which are set by the modeller and can have a significant impact on the answer. With the lack of experimental data this does leave a question on the reliability and robustness of modelling tools.

13.2. Key Research Gaps

- There are distinct phenomena where a lack of experimental data is impacting the development of modelling tools, listed below.
    - Lack of experimental data to provide liquid-surface interface behaviour under dynamic conditions.
    - Lack of experimental data to validate evaporation models, especially under dynamic conditions.
    - Lack of experimental data to validate LH2/GH2 two phase flow in pipelines and within components.

  - Lack of experimental data for supercritical hydrogen and flow behaviour through components and systems.
- Commercial CFD codes unable to capture experimentally observed ullage compression behaviour.
- Due to the lack of validation data there are sub-models, within both commercial and bespoke simulation tools, that require the setting of a parameter, for which there is no guidance on the value that should be used.

13.3. Key Research Groups

Institution/Company	Country	Topic
University of Western Australia	Australia	BoilFAST https://www.fsr.ecm.uwa.edu.au/software/boilfast/
CEFACS AVBP DNS code	France	https://www.cerfacs.fr/avbp7x/
Adrea-HF	Greece	Erel » ADREA-HF
Gexcon	Norway	FLACS https://www.gexcon.com/software/flacs-cfd/
HYSAFER, Ulster University	UK	https://www.ulster.ac.uk/research/topic/built-environment/hydrogen-safety-engineering
Ansys	USA	https://www.ansys.com/en-gb Commercial engineering simulation tool.
C&R Technologies	USA	https://www.crtech.com/products/thermal-desktop https://www.crtech.com/products/sindafluint
HYPER Lab, Washington State University	USA	https://hydrogen.wsu.edu/modeling-and-simulations/
NumFOCUS Cantera	USA	https://numfocus.org/ for Cantera https://numfocus.org/project/cantera https://www.cantera.org Originally developed California Institute of Technology
OpenFoam ESI group, Keysight Technologies	USA	https://www.openfoam.com/ https://www.esi-group.com/
Sandia National Laboratories	USA	HyRAM + HyRAM+ – Energy
Siemens		Star-CCM+

13.4. Narrative

All of the simulation tools described below are reliant on a limited data set to validate key behaviours in liquid hydrogen, such as boil off, vapour-liquid interface, flow of multiphase or supercritical hydrogen. There are some models, for instance boil off, where a coefficient is used as a multiplier on key equations, this coefficient being fitted to experimental data. This approach demonstrates the immaturity of modelling available currently and the over-reliance on a very limited experimental data set. Whilst single phase static conditions are generally well understood, and modelled, there are significant areas of the physics of liquid, multiphase and supercritical hydrogen behaviour that are not sufficiently characterised to provide robust modelling of cryogenic hydrogen storage and fuel system without the validation from sub-system or system level testing.

13.4.1. High Fidelity Numerical Modelling Tools

Missey et al., (2024) [178], have utilised the Direct Numerical Simulation (DNS) AVBP code from CERFACS to investigate the impact of stratification on the propagation of a flame front above a liquid H2 pool, comparing to theoretical predictions. This indicates that DNS models are in use for LH2 but remain too computationally expensive for full system modelling.

Kangwanpongpan et al., (2024) [179] used Ansys to provide a Large Eddy Simulation (LES) for pressurised venting from a tank, whilst Indelicato et al., (2023) [180], have used OpenFOAM as the base code for their LES study of LH2 flows through pipework. The use of CFD codes to utilise LES is a common trend, allowing more detailed analysis where appropriate.

A very recent PhD description from University of Melbourne & CSIRO is looking to integrate high fidelity sub-models within CFD, project end date is 2027.

13.4.2. RANS CFD

There are both commercial and open source CFD tools that have been utilised for modelling LH2. The main commercial tools are Ansys (Perng, 2024 [181]), Siemens's Star-CCM+ and FlowScience's Flow3D. The paper by Pesich et al., (2023) [182], compares the performance of Ansys Fluent, Siemens Star-CCM+ and Flow3D for a liquid hydrogen no vent fill. None of the codes were able to capture the ullage compression at the end of the fill and there were significant variations in performance for different physical phenomena modelled.

Openfoam is an open source tool that Mohammadpour & Salehi, (2024) [183] used to model cryogenic hydrogen release, whilst Liang et al., (2024) [184] used it to model non-ignited releases.

FLACS is a specialised CFD tool for modelling dispersion of hazardous materials, fire and explosion, it is provided by GEXCON, https://www.gexcon.com/software/flacs-cfd/ Amaral et al., (2024) [185] provides a recent example of the use and adaption of this code.

ADREA-HF was developed by Environmental Research Laboratory, Institute of Nuclear Technology & Radiation Protection, National Centre for Scientific Research, and has been used for Boiling Liquid Expanding Vapour Explosion (BLEVE) modelling most recently by Ustolin et al., (2022) [186].

Matveev & Leachman, (2023) [187], [188] use Star-CCM+ to provide modelling of the ullage space with a reduced order model used for the liquid hydrogen and vent space when modelling a cooling approach of endothermic ortho-para conversion. This combined model approach enables a reduction of compute time.

13.4.3. Bespoke Modelling Tools

Cantera (Goodwin et al., 2023 [189]) is an open-source code that includes chemical kinetics, thermodynamics and transport calculations that can be edited to include detailed sub-models. Cantera has been used for modelling combustion for LH2 by Lv et al., (2025) [190] to provide one example.

Modelling of solid air in liquid hydrogen has been modelled using Lattice Boltzmann combined with cellular automation (Zheng et al., 2023 [146]) and more recently by a two dimensional quantified phase field model discretised by an isotropic difference method (Lv et al., 2025 [190]).

BoilFAST is an open-source code developed by the Fluid Science and Resources research group at the University of Western Australia that can simulate boil-off from cryogenic liquids in a storage tanks. Al Ghafri et al., (2022) [191] is one example where this software has been used to model LH2 boil-off.

13.4.4. Low Order, 1D/System Modelling Tools

Hyram (Ehrhart et al., 2021 [192]) was developed by Sandia National Laboratories to provide a tool for risk assessment and consequence modelling. Saini et al., (2025) [193] have extended the HyRAM code to enable the explicit definition of the Gaussian temperature profile within the self-similar region, as well as coupling the energy equation with a real-gas equation of state, providing more accurate state properties of H2-air mixtures.

Mathworks provides an example within their published documentation for Simscape of liquid hydrogen storage modelling, this provides a system level modelling approach.
https://uk.mathworks.com/help/hydro/ug/LiquidHydrogenStorageAndTransportationExample.html

Sindia/Fluint is a code provided by C&R Technologies as part of the thermal desktop tool.

There are a few papers that have been published on modelling full LH2 fuel systems, the most recent being Boryaev et al., (2022) [81] & Thilker et al., (2024) [194].

In summary there are a range of developed simulation/modelling tools that are available, both open-source and commercial. However, all tools are dependent on fundamental understanding of LH2 thermofluids, which as highlighted in sections 0-0 are often incompletely understood, particularly for multiphase flow. There are other areas where validation data simply does not exist (details of boil-off spatial variation across liquid-vapour interfaces). This combination of a lack of fundamental understanding and data means that LH2 modelling tools require development before they can be utilised for full system design. The development of these simulation/modelling tools must continue, building on increased fundamental research and validation, to ensure that future model-based systems are available for product development to ensure LH2 deployment timeframes are met.

14. Scenarios; Normal Operating and Upset Conditions

Whilst scenarios are not low TRL research, a review of available research for six scenarios has been included to demonstrate the maturity of technology for cryogenic hydrogen storage and fuel system. These scenarios utilise these fundamental properties that have been reviewed within this report to understand how the gaps effect higher level system research and development.

The six scenarios covered in this review are: refuelling, stratification, pumping, chill down, sloshing and boil-off. Other scenarios, such as vacuum breach, leakage, spills and other scenarios relevant to using LH2 have not been considered as part of this report.

Key research groups are collected for all scenarios in a table within section 14.7.

14.1. Refuelling

14.1.1. Overview

LH2 refuelling is the process of transferring LH2 into a storage or fuel tank. The refuelling process involves specialised equipment to handle the cryogenic temperatures and prevent evaporation or leakage, ensuring safe and efficient transfer. This technology is crucial for hydrogen fuel cell vehicles and is a key component in developing hydrogen as a clean energy source for transportation and industry.

Key challenges for LH2 refuelling development are infrastructure development, cost reduction, and ensuring safety due to the cryogenic nature of LH2 and its high flammability.

LH2 refuelling into a partially filled tank is closely connected to both stratification (section 14.2) and chill down (section 14.4), as the introduction of colder liquid hydrogen interacts with the warmer fluid within the tank, leading to thermal gradients and phase changes. Research in this area focuses on understanding these interactions to optimise refuelling strategies, minimise stratification-induced pressure buildup, and improve chill down efficiency. It is also directly related to boil-off since refuelling process inevitably has LH2 boil-off losses, which are typically advised to be captured and potentially recycled.

Recommended papers that review refuelling are Bauer et al., (2019) [195] , Genovese et al., (2023) [196], Mayer et al., (2019) [197], Kikukawa et al., (2009) [198] .

14.1.2. Research Gaps

LH2 refuelling is an important subject, in particular, due to the safety aspect for which the reader is directed to the Cryogenic Hydrogen Health and Safety Global Research Landscape report. The two main research gaps that need further and deeper study in the future are:

- Experimental data on the behaviour of refuelling systems and components to provide both simulation validation and insight into the behaviour of the complex flows within refuelling components and systems.
- Development of simulation tools to accurately and robustly capture the complexity of LH2 refuelling components and systems.

14.1.3. Narrative

While some road vehicle hydrogen refuelling stations, particularly in regions like Japan, Europe, Republic of Korea and the USA, support both gaseous and LH2, the overall network is limited. Significant research and investment are ongoing to improve the efficiency, safety, and scalability of LH2 refuelling to make it a practical option for widespread use in transportation, particularly for heavy-duty vehicles and aerospace applications.

Most of the research on LH2 refuelling so far has been concentrated on either technology advancement or infrastructure assessment, i.e. technical and economic analysis. Much of the research has related to road vehicles, with a few papers providing conceptual level assessment of aviation refuelling. Recommended papers, that directly relate to aviation, include Mangold et al., (2022) [199] reported that the refuelling process of LH2 requires additional process steps compared to a conventional fuel, e.g. purge and chill down. However, Mangold et al., 2022 [199] calculated a turnaround time for LH2 as being comparable to Jet-A refuelling times. Usage of a semi-automated LH2 refuelling system is suggested (Mangold et al., 2022 [199]), similar to the type that already has been studied and used in the automotive industry. There remain practical challenges around refuelling time, management of boil-off, and airport operational health and safety requirements, i.e. exclusion zone sizes.

Research of LH2 refuelling addresses the following areas:

- Refuelling infrastructure and technology: The development of hydrogen refuelling stations (HRS) focus on the technologies involved from hydrogen production to the final refuelling stage.
- Innovations in refuelling systems to improve efficiency and/or cost: Research has been conducted on fast refuelling technologies for hydrogen storage systems. Advancements such as Toyota's self-pressurising LH2 system (LH2 system design that includes a self-pressuriser that converts a proportion of boil-off gas from LH2 back into usable fuel without external energy, enhancing efficiency and sustainability) have been introduced to address boil-off challenges during refuelling.
- Safety and risk assessment: Comprehensive reviews have been conducted on the safety aspects of LH2 use, highlighting concerns such as hydrogen leakage, explosion risks, and the need for robust risk assessment methods at refuelling stations.

14.2. Stratification

14.2.1. Overview

Stratification occurs when hydrogen forms layers with varying temperature and density, especially in large storage tanks or confined spaces. Thermal stratification, which is the main focus of research on LH2 stratification, refers to the formation of a thermal gradient inside a storage tank. Stratification can also lead to large variation in fluid conditions when LH2 is withdrawn from the storage tanks. Researchers are exploring solutions such as enhanced tank mixing designs, advanced sensors for real-time monitoring of hydrogen distribution, and computational fluid dynamics models to predict and mitigate stratification. These advancements aim to ensure uniform hydrogen dispersion, improving system performance and safety.

Key issues in the research of LH2 thermal stratification include understanding the complex heat transfer processes, phase transitions, and fluid dynamics under cryogenic conditions, as well as addressing the effects of tank geometry, insulation, and external factors like vibration or gravity variations. Additionally, there is a lack of experimental data for validation, particularly for advanced CFD models and unique operating scenarios, which poses significant challenges to achieving accurate and comprehensive insights.

Readers can gain valuable insights into thermal stratification from the experimental study by Jurns et al., (2001) [200], which demonstrates an example of experimental work in this area. Additionally, the numerical study by Liu et al., (2018) [201] represents one of many CFD papers focused on a specific case (in this instance examining sloshing affecting thermal stratification).

14.2.2. Research Gaps

Research to date has explored a wide range of conditions under which LH2 tanks are used. However, in order to advance LH2 technology further and enable its potential application in aviation, several underexplored aspects of LH2 thermal stratification require additional study:

- Dynamic operational conditions: Scenarios such as tank filling, emptying, or rapid pressure changes are not well studied, with most research focusing on static conditions.
- External motion and environmental influences: The effects of external factors like vibration, ambient heating, rotational forces, and varying inertial loads on stratification remain underexplored.
- Non-ideal tank geometries: Research has largely concentrated on simplified or standard tank geometries, leaving stratification behaviour in tanks with complex shapes, insulation irregularities, or multiple compartments inadequately investigated.
- Multi-tank systems and large-scale applications: Studies on multi-tank systems and large-scale industrial storage facilities are limited, particularly regarding the interaction of stratification across interconnected tanks.
- Advanced cooling and mixing strategies: Strategies such as active mixing, innovative spray cooling systems, or novel heat exchanger designs remain largely unexplored, despite their potential to disrupt or control stratification effectively.
- Material-specific stratification studies: Limited research exists on how stratification interacts with advanced tank materials, coatings, or insulation systems, particularly under long-term operational conditions.

14.2.3. Narrative

Research of LH2 stratification addresses the following areas:

- Heat transfer and flow dynamics: Investigations into the physics of the process, to understand and manage thermal gradients and liquid-vapour interactions that contribute to stratification.
- Tank design and insulation: Research into how tank geometry, materials, and insulation methods affect the development and suppression of thermal stratification.
- Safety and operational efficiency: Studies on how stratification influences pressure build-up, boil-off rates, and overall energy efficiency in storage and transport systems.
- Numerical modelling and validation: Development of CFD models to simulate stratification, with efforts to validate these models against experimental data for improved accuracy and predictive capability.

- External factors and environmental conditions: Exploration of how factors like vibration, varying inertial loads, and ambient temperature fluctuations impact thermal stratification, particularly in dynamic operational environments.

Research to date on LH2 stratification can be divided into two distinct periods. The first, from the early 2000s, primarily relied on analytical mathematical models to predict thermal stratification, often validated against experimental data from NASA or other earlier studies. This research was predominantly conducted in India and the USA.

The second period, spanning the last decade, is characterised by the widespread use of CFD simulations. These recent studies, largely originating from China, explore a variety of parameters such as non-isothermal tank conditions, varying inertial loads, supercritical heating, and the use of rotatable sprayers, each requiring unique setups. However, some of these studies remain unvalidated due to a lack of experimental data for such specific scenarios, with others relying on experiments from the 1960s or, less commonly, more recent data.

Currently, there appears to be a gap in comprehensive and accurate studies, whether experimental or numerical, focused solely on thermal stratification. Nevertheless, aspects of stratification are partially addressed in broader research topics such as boil-off management, energy efficiency, tank insulation, and heat transfer within tanks. Advancements are needed in the underexplored areas described in the research gaps subchapter.

14.3. Pumping

14.3.1. Overview

The pumping of liquid hydrogen involves transferring it using specialised cryogenic pumps that need to operate efficiently at extremely low temperatures without freezing or leaking. These pumps are designed to handle the effects of low temperature on materials and require special seals to prevent leaks. LH2 pumping is crucial in aerospace, hydrogen energy systems, and scientific research.

Pumping, as a topic, overlaps with Refuelling (section 0) and Work (section 0). Here, pumping is defined as a broader term for transferring the liquid, while refuelling is a specific application of pumping, aimed at loading sufficient fuel into storage tanks on the aircraft to cover mission demand.

14.3.2. Research Gaps

Published numerical and experimental research does not demonstrate maturity, with incomplete data available for both understanding phenomena and providing validation. Liquid nitrogen has been used in place of liquid hydrogen for some experimental work.

The key research challenges for improving pump performance and extending their lifespan are:

- Materials development optimisation for durability, especially in tribology and sealing.
- Optimisation for efficiency, overall performance, thermal management.
- Optimisation for cavitation control, safety, scalability, and cost-effectiveness.

14.3.3. Narrative

Research of LH2 pumping addresses the following areas:

- CFD.
- Experiments.
- Analytical models to reduce both the production cost and the power consumption.
- Technoeconomic assessment.
- Consideration of aerospace specific applications such as lightweighting, safety, robustness and durability.

For the majority of papers reviewed, the focus was on improving the pump performance by reducing both hydraulic losses and cavitation effects. A variety of pumps were considered: piston pump, volumetric scroll pump, submerged pump, centrifugal pump, and turbopump (Kim et al., 2024 [202] ; Kritmaitree et al., 2004 [203] ; Ku et al., 2022 [204]; Lai et al., 2023 [205]; Shao & Zhao, 2024 [206]). Not all papers contain validation of CFD results. Several papers used liquid nitrogen in their experiments as a starting point, noting that use of LH2 was planned in future work.

Research on LH2 pumps can be grouped into five key categories:

- Materials and durability: Development of advanced materials for cryogenic temperatures to improve pump component strength, reduce wear, and ensure long-term reliability and durability.
- Efficiency, performance, and thermal management: Enhancing energy efficiency, optimizing pump designs, improving flow rates and pressure capabilities, and advancing thermal insulation and cooling systems to prevent hydrogen vaporization and reduce power consumption.
- Cavitation control: Investigating methods to prevent cavitation, optimising pump design and fluid dynamics to maintain stable operation and prevent damage.
- Safety: Developing leak detection systems and safety mechanisms to handle hydrogen's flammability and ensure safe pump operation in cryogenic conditions.
- Scalability and application: Researching scalable pump systems for large-scale applications, ensuring reliable performance under varying conditions, and optimizing for use in industries like aerospace, transportation, and energy.

Although papers exist considering LH2 pumps, there is scope for more comprehensive research to be performed analytically, experimentally, and numerically. It is especially valid given that there are many diverse types of LH2 pumps, and they are likely to require different simulation and optimisation approaches.

14.4. Chill down

14.4.1. Overview

Liquid hydrogen chill down refers to the controlled process of cooling down equipment, pipelines, or storage vessels to cryogenic temperatures. This process ensures that the equipment reaches a stable temperature where hydrogen remains in its liquid state. Chill down is crucial in cryogenic equipment to prevent excessive boil-off, minimise thermal stresses, ensure safety, and maintain the integrity of the equipment.

Key issues in liquid hydrogen chill down include thermal stratification and cavitation in pumps and pipelines. Thermal stresses pose challenges to system durability and efficiency. Effective cooling strategies are needed to minimise energy consumption, cool-down time, and uneven cooling. Safety concerns, such as flammability, pressure buildup, and leak management, are critical, alongside scalability for industrial applications. Optimisation of materials, system design, and operational processes is essential to enhance performance, reduce costs, and ensure reliability in LH2 systems.

Most research on LH2 chill down is performed experimentally, initially on LN2, later on NASA performed experiments using LH2 (Rame et al., 2014 [207]; Hartwig et al., 2019 & 2020 [208, 209]); the rest of the research papers include analytical and mathematical models as well as CFD. Recommended papers to get more familiar with chill down topics are Ahuja et al. (2024) [210] , Banica & Wisse (2013) [211] and Umemura et al. (2019) [212].

14.4.2. Research Gaps

In comparison with the other scenarios, chill down appears to be fairly developed in terms of research. This is due to the chill down topic being investigated by various aerospace agencies throughout the years, including NASA. Half of the papers in the scope (of 14 papers) performed experiments; in three papers there are CFD studies, and four papers cover computational calculations using mathematical and analytical models to provide insights into chill down operation, its design recommendations and accurate modelling strategy. Additionally, a research group from NASA have been working on the chill down topic for multiple years and published detailed papers, including experimental studies (e.g., Hartwig et al., 2019, 2020 [208, 209])

Remaining research gaps include:

- Experimental data – there is a fair amount of experimental research; however, it does not appear to cover a wide range of parameters. For example, Hartwig's team has focused on high Reynolds numbers, while a significant portion of studies used liquid nitrogen (LN2) instead of liquid hydrogen (LH2).
- Accurately simulating heat transfer, multiphase flow, phase change, and cavitation in cryogenic conditions. All modelling approaches rely on assumptions within sub-models, determined by the CFD modeller. Furthermore, experiments do not encompass the full range of conditions needed for comprehensive validation across various cases. Ahuja et al. (2024) [210], obtained accurate results in their numerical models validated against experiments by Hartwig et al.(2020) [209]. However, Ahuja et al. [210] concluded that more studies are needed to understand how the annular quench fronts observed in some liquid hydrogen tests evolve.
- Experimental data needs to precisely record boundary conditions, including the behaviour of materials under cryogenic temperatures and the effects of thermal gradients, without this, simulations are based on assumptions which can invalidate the model.

14.4.3. Narrative

The key areas of research on chill down are:

- Heat transfer and thermal management (e.g., Hartwig et al., 2016, 2019, 2020 [208, 209], [176]). Research focuses on development of accurate numerical methods for optimising heat transfer during chill down; experimental work typically shows thermodynamic state diagrams with pressure drop calculations used to show the evolution of the LH2 chill down process along the transfer line. Fundamental heat transfer characteristics for various experiments are also examined to show how inlet liquid temperature and flow rate affect LH2 chill down.

- Materials and structural integrity (e.g., Takeda et al., 2017 [213]). Studies explore material behaviour under cryogenic conditions, addressing thermal stresses and durability. Research to both reduce stresses and research into structural integrity to mitigate damage from rapid temperature changes is underway.
- Flow dynamics and efficiency (e.g., Hartwig et al., 2020 [209]; Ahuja et al., 2024 [210]). Flow dynamics research examines turbulence, multiphase flow, and cavitation to provide insights to the chill down process and reduce chill down times by improving energy efficiency.
- Safety and risk management (e.g., Flachbart et al., 2013 [214]). Ensuring safety during chill down involves managing hydrogen's flammability, detecting leaks, and controlling pressure build-up. Research also addresses cavitation damage and vibrations to enhance system stability and operational safety.

Overall, multiple experiments have been performed on LH2 chill down, with analytical and numerical models utilised and published.

CFD has been utilised less than other methods. However, CFD simulations of chill down are quite complex due to several factors: accurately simulating heat transfer, multiphase flow, phase change, and cavitation in cryogenic conditions. Additionally, the need for transient and spatially precise boundary conditions, including the behaviour of materials under cryogenic temperatures and the effects of thermal mass and gradients, makes simulations computationally intensive as well as requiring detailed information on infrastructure/hardware. Therefore, while CFD simulations are a powerful tool for understanding and optimising LH2 chill down, they require advanced expertise and significant computational resources to ensure accurate results. An additional significant challenge in CFD is that chill down in other liquids, including liquid nitrogen, have very different characteristics (Ahuja et al., 2024 [210]) to LH2. Hence simulation tools are limited due to the lack of fundamental experimental data for LH2 on which to build the correct modelling physics.

14.5. Sloshing

14.5.1. Overview

Liquid Hydrogen sloshing refers to the movement and oscillation of LH2 within a container or tank, often caused by external forces, e.g. acceleration, vibration, or sudden changes in motion. Sloshing presents particular risks in cases where tanks are at low fill levels; in these cases rapid fluid movement can cause high loading on tanks structures and when hydrogen is stratified within tanks sloshing can cause vapour collapse and rapid depressurisation. Research of sloshing helps in designing tanks and control systems to minimize risks, ensure stability, and improve the efficiency of handling liquid hydrogen in dynamic environments.

Recommended papers that summarise research on sloshing are by Zhu et al. (2024) [215] and Hauser et al. (2024) [216] .

14.5.2. Research Gaps

Despite recent advancements, gaps persist, especially in understanding the interaction between turbulence, phase change, and the evolving liquid-vapor interface under dynamic conditions. Existing models often underpredict pressure drops and mist effects, highlighting the need for more comprehensive simulations that account for complex variables in multi-phase, multi-dimensional flows. Additionally, there is a need for better modelling of sloshing in response to external influences like vibrations or acceleration.

Experimental data to capture the interaction between turbulence, phase change, and the evolving liquid-vapor interface under dynamic conditions is required, along with data to validate models under a wide range of real-world conditions, including vibrations or acceleration, which are relevant for aviation conditions.

14.5.3. Narrative

Research on cryogenic fluid sloshing, particularly LH2, has focused on pressure drops, turbulence production, heat exchange, and phase change. Early studies, like Himeno et al. (2007) [217], numerically and experimentally investigated sloshing using water and surface deformation under varying gravity conditions. Later works, such as Takeda et al. (2015) [218], expanded this to LH2, attempting to improve the CFD model by including phase changes, though challenges like turbulence estimation and mist effects remained. More recent studies, such as those by Jeon et al. (2024) [219], have enhanced phase-change modelling, improving the accuracy of simulations in predicting boil-off and thermodynamic characteristics. Among the mentioned studies, Himeno et al. (2007) [217] and Jeon et al. (2024) [219] validated their models against experimental data, while Takeda et al. (2015) [218] conducted only an initial CFD model assessment.

Despite advancements, several complexities persist in understanding LH2 sloshing. One significant challenge is accurately modelling the interaction between turbulence, phase change, and the evolving liquid-vapor interface during dynamic sloshing events. Running and validating CFD simulations of LH2 sloshing is complex due to the highly dynamic and nonlinear interactions between liquid, vapor, and tank walls, requiring precise interface tracking and turbulence modelling. In addition, due to the scarcity of experimental data sub-models cannot be validated.

Existing CFD models often underpredict pressure drops and fail to fully account for mist formation, which affects evaporation and condensation processes. Additionally, variations in external conditions, such as vibrations or acceleration, add further complexity. There is also a lack of comprehensive data for validating models under a wide range of real-world dynamic conditions, which hinders the development of more robust and accurate simulations.

The research has made significant strides in understanding LH2 sloshing and its impact on tank pressure and boil-off rates, but gaps remain, particularly in modelling the complex interactions of phase change and turbulence.

Key research groups, including those from Tokyo and NASA, have made substantial contributions to improving CFD simulations and validating them against experimental data. However, there is a continued need for more advanced turbulence models and a deeper understanding of how sloshing interacts with other dynamic factors, such as tank geometry and external accelerations. Further research in these areas is crucial for optimizing LH2 storage and transport systems, particularly for applications in propulsion and space exploration.

14.6. Boil-off

14.6.1. Overview

Liquid hydrogen boil-off refers to the phenomenon where LH2 evaporates into gas due to heat transfer from the environment, even when stored in insulated containers. Studying boil-off is important for understanding the rate of LH2 transitioning to its gaseous state, impacting storage efficiency, transportation, and fuel management. This research can help develop better insulation techniques, minimise losses, and optimise the storage and handling of LH2 in various applications.

The main issues with LH2 boil-off in research involve managing heat ingress into storage tanks, causing vaporisation and pressure build-up. Storage tanks require effective pressure relief and venting systems (Matveev & Leachman, 2023 [187]). Unmanaged boil-off can reduce efficiency, increase operational costs, and pose safety risks.

Recommended papers for this topic are Matveev & Leachman (2023) [187, 188], Hastings et al. (2001) [221] and Zuo et al. (2021) [220].

There is overlap with section 0, as the boil-off process falls under the multiphase category and faces similar challenges, including a lack of experimental data for validation and the need for CFD model improvements due to the limited research conducted on this topic.

14.6.2. Research Gaps

- There is a lack of experimental data covering a wider range of parameters required to study boil-off in detail and conditions for aviation.
- This lack of data has impacted numerical modelling development of boil-off as noted in section 0.

14.6.3. Narrative

The number of experiments performed on LH2 boil-off is quite limited. Most of the CFD researchers chose to validate their models against reliable NASA experiments. Numerous modelling studies validated their findings using NASA's experimental data from a multi-purpose hydrogen test bed (MHTB), which was summarised by Hastings et al. (2001) [221] . Similar in design to a full-scale cryogenic tank for space applications, this tank was widely utilized for experiments by NASA.

Models range from 1D analytical models (prevalent in the early 2000s, although some recent publications) to more advanced 2D CFD simulations but rarely 3D CFD simulations. Across all model types, essential parameters directly influencing the solution are the tank design, fluid properties, fill levels, initial temperatures, and internal flow conditions. Three primary challenges for the CFD modelling of boil-off are accurate definition of thermal boundary conditions, accurate setup of temperature-dependent fluid properties, and appropriate selection of the phase-change models. All are critical for capturing the complex behaviour of cryogenic systems.

Accurate modelling of heat transfer paths is essential for reliable predictions. Fluid properties require initial heat partitioning between the liquid and vapor phases (Haoren et al., 2023 [222]). This study proposed a theoretical framework to calculate heat distribution based on fluid properties, tank geometry, and fill levels. Similarly, selecting an appropriate phase-change model is crucial for capturing the underlying physics, which depend on fluid behaviour, phase-change mechanisms, and the dynamics of heat transfer-driven pressurisation. Wang et al. (2024) [223] additionally pointed out challenges related to assumptions regarding ortho-para hydrogen isomer ratios and the integration of external cold sources for long-term storage. There is limited experimental data available for both aspects, which calls into question the accuracy of models used in self-pressurising tank simulations.

Ratnakar et al. (2021) [27], in their overview, highlighted key technological gaps in liquid hydrogen storage and transport, particularly in comparison to liquefied natural gas. These gaps exist because of factors such as higher boil-off rates, insufficient insulation systems, limited large-scale designs, and a lack of comprehensive data. They suggest that extensive experimental and modelling studies are required to address these gaps, across a broader cryogenic temperature range to optimise insulation strategies and tank designs. Additionally, further research is required to improve hydrogen safety under cryogenic conditions, in particular relating to embrittlement and thermal cycling, in order to ensure safe and reliable large-scale implementation of the LH2 supply chain.

Five areas of challenge for modelling self-pressurising tanks were noted in Wang et al, 2024 [223] . These are summarised below with information included from other works:

- Transient behaviour of heat leakage – in particular, managing the cold end temperature from 20 – 300 K to allow understanding of the transient heat leakage for boil-off/self-pressurisation.
- Spatial distribution of heat leakage – heat leakage flux is not uniform in tanks; there is a difference impacted by the phase of hydrogen and the material of the tank and system linkage points.
- Vapour – liquid interfacial mass transfer – correlations are generated from steady state experiments measuring temperature gradient across the interface. This does not take into account the time of storage and modellers often tune correlations to match observed behaviour.
- Geometric structure and volume of the tank – limited experiments of expected tank shapes, i.e. NASA tests consider spherical tanks where aircraft tanks are expected to be cylindrical.
- Integration of inner heat source and external cold source – to model boil-off assumptions are often made regarding percentage of ortho-para isomeric forms. Clear information at the beginning of storage would provide a better initial condition and allow inner heat source models used to capture conversion, to be used more appropriately. There are some approaches that suggest integrating external cold sources in tanks for long term storage, but little experimental data is available on this.

After performing a bibliometric analysis, Wang et al. (2024) [223] concluded that the key gaps and challenges include improving experimental measurement techniques, enhancing numerical simulation efficiency through artificial intelligent integration to reduce computational costs and considering additional practical factors in both experimental and simulation studies to comprehensively understand the processes.

14.7. Key Research Groups for All Scenarios

Institution	Country	Topic
Argonne National Laboratory (Reddi et al., 2017 [224])	USA	Refuelling Research LH production, cryogenic storage, and distribution, focusing on improving storage systems, fuel cell performance, and infrastructure. Their work also includes safety protocols, materials development, and advanced monitoring technologies for efficient and secure hydrogen use.
Air Liquide (Carrere et al., 2021 [225])	France	Refuelling Conducts research on liquid hydrogen production, storage, and distribution, focusing on improving cryogenic tank designs, enhancing hydrogen liquefaction processes, and developing efficient refuelling infrastructure. Their work also includes advancing safety measures, optimising hydrogen delivery systems, and scaling up liquid hydrogen technologies to support sustainable energy solutions across industries, particularly in transportation.
Lawrence Livermore (Petitpas et al., 2018; Petitpas & Aceves, 2018 [226])	USA	Pumping Perform advanced simulation, high-performance computing, and experimental tests to optimise materials and tackle technological challenges in hydrogen production, storage, and energy systems.
Japan exploration aerospace agency (Umemura et al., 2019 [212])	Japan	Chill down Develops the technologies to control and supply LH2 fuel precisely in the research on rockets and hypersonic passenger aircraft using recent technologies for development of LH2-fuelled aircraft.
University of Tokyo (Umemura et al., 2019 [212])	Japan	Chill down Performs research of hydrogen energy systems that use renewable energy to produce hydrogen for both storage and use. In addition, to construct a regionally distributed energy system for the future, the researchers are focusing on a combined energy system using renewable energy + hydrogen energy + batteries, whilst utilising AI prediction technology.

Institution	Country	Topic
University of Florida (Hartwig at al., 2015 [227]; Hartwig et al., 2019 [208])	USA	Chill down Research in partnership with NASA, focussing on improved hydrogen production processes, terrestrial and in-space cryogenic transport and storage.
Indian Institute of Technology Madras (Khurana et al., 2006 [228]; Kumar et al., 2007 [229])	India	Stratification Involved in advancing technologies on hydrogen production, storage, and utilisation, with a focus on green hydrogen and sustainable energy solutions.
Tsinghua University (Ji et al, 2018 [230])	China	Focuses on developing efficient supercritical hydrogen storage and transportation technologies, aiming to enhance storage density and safety.
Clausthal University of Technology (Samara et al., 2024 [231])	Germany	Conducts research on technologies to produce hydrogen from renewable energy sources based on AI with optimised costs for environmental applications.
The Commonwealth Scientific and Industrial Research Organisation	Australia	Ongoing projects primarily focus on zero or low-emissions; individual projects encompass the full hydrogen value chain.
H2Fly, Daimler Truck, Linde	Germany	These are leading companies in Germany; potentially not all of their research is openly available.
Marshall Space Flight Centre (Cross et al., 2002 [232]; Flachbart et al., 2013 [214]; Jurns et al., 2001 [200] ; Hartwig et al., 2020 [209]; Ahuja et al., 2024 [210]; Pesich et al., 2023 [182]; Umemura et al., 2019 [212])	USA	Chill down, stratification, boil-off. Large number of papers of good quality research on various topics; includes both experimental and numerical work.

15. Conclusions

A gap analysis has been undertaken to identify areas where further research and development is needed to understand the fundamental thermofluid behaviour of LH2, including its interaction and transition to other phases. Throughout the report sixty-one research gaps were identified. Forty-three of these relate to fundamental research, the remaining eighteen being within the final section where scenarios, which utilise these fundamental properties, have been reviewed to understand how the fundamental gaps effect higher level system research and development.

A comprehensive understanding of LH2, both from experimental and modelling perspectives, is vital for hydrogen powered aircraft. In order for cryogenic hydrogen storage and fuel system on aircraft to be airworthy, they need to be optimised for weight and efficiency, but they also need to be certified. The path to certification requires proof of a clear understanding of the system as it is meant to operate but also in unexpected conditions. All of this work will be built upon the fundamental data and understanding of LH2.

Most of the experimental data on fundamental properties such as density, dielectric constant, and more, was gathered in the United States in the mid twentieth century. The data sometimes has uncertainties and is not always self-consistent, particularly around phase change boundaries. These datapoints are in the NIST database, which is frequently used in modelling software to represent hydrogen, leading to a lack of robust simulation tools. There is a research gap for new measurements, which use standardised testing procedures and more modern sensing equipment, to minimise the uncertainties around this experimental data.

The majority of the fundamental experimental work with LH2 is focussed in the United States and Japan on a select number of research groups. These research teams are investigating areas such as heat transfer, ortho-para conversion properties, and acoustics. Some experimental characterisation of supercritical hydrogen has linked with Germany and China as well through neutron moderators and experiments. However, the literature search has shown that beyond the active groups in Japan and the United States, there are few laboratories with suitable experimental setups for gathering fundamental property data on LH2.

Most of the papers found on LH2 research in the past ten years have focussed on modelling. Much of the work has been incremental and has focussed on the use of LH2 properties to develop scenarios or designs for product uses. The options of modelling software, both in terms of type of modelling and software providers, are numerous but all require a deep understanding of the systems that are being modelled and the limitations of the software. For example, many models have a tuneable parameter to be set by the modeller, which has a significant effect on the model outcome. Experimental data with lower levels of uncertainty would allow models to minimise the tuning parameters required by the user.

15.1. Summary of Research Gaps

A summary of identified research gaps provided within this report for fundamental thermofluids is listed below by area.

Fundamental ortho-hydrogen and para-hydrogen research gaps include:

- A large number of academic papers are experimental, unlike in most other fields with LH2. However, there is still a need for a more comprehensive and fundamental understanding of the spin conversion causes when affected by catalysts and other activation mechanisms.
- Despite a large amount of work on ortho-para hydrogen, there is a lack of a universal kinetic model for the catalyst-assisted conversion reaction, hindering the development of accurate predictive models for ortho-para conversion reactors; this includes quantitative descriptions of cooling requirements and system pressure loss.
- Research focussed on understanding ortho-para hydrogen conversion is limited, partly due to its multidisciplinary nature. Research of nuclear spin isomers lies at the intersection of multiple scientific disciplines, including surface and solid-state physics, molecular spectroscopy, magnetism, thermodynamics, chemical kinetics, and the study of irreversible processes. This demonstrates the need for research groups with researchers with a wide spectrum of knowledge.

Fundamental fluid properties research gaps include:

- Experimental measurement and data of fundamental properties, particularly using modern sensors and consistent experimental design to minimise uncertainty and data scatter. More experimental information on the following fundamental properties is of particular interest:
    - Viscosity.
    - Vapour pressure, including the vapour-liquid interface.
    - Surface tension (which links with the vapour-liquid interface).
- Experimental data at phase change boundaries and in complex flows
    - Behaviour of fundamental properties in dynamic systems varies from that of static systems, the latter of which form the basis of most historical experimental design.
- Multiphase behaviour of liquid hydrogen when encountering sudden expansions, large pressure or thermal gradients, including transient behaviours at points of change.
- Combined experimental and modelling analysis of system/component level analysis to provide methodology development, validation data and to enable monitoring and control approaches to be investigated.
- Experimental studies of alternative low energy liquefaction approaches, providing validation data for modelling.
- The behaviour of hydrogen near and at the critical point is not well characterised, including the transition dynamics between liquid, gaseous, and supercritical states.
- Supercritical hydrogen is known to penetrate materials more readily than gaseous hydrogen. The interaction between supercritical hydrogen and relevant materials requires further experimental investigation.

Fundamental heat research gaps include:

- There is limited experimental data, often from same sources (experimental facilities/researchers). Sub-cooled and supercritical data is limited. There is recent experimental data on flow boiling and two-phase heat transfer coefficient and universal critical heat flux. Unfortunately, not all this recent data is not publicly available.
- There is a lack of aviation specific research on the effects of heat transfer (effects of vibrations, pulsed flow etc).
- There is a lack of facilities that can conduct experiments with LH2 to produce robust data.

Fundamental work research gaps include:

- There is limited experimental data available for cavitation in liquid hydrogen, with most from NASA in 1970s.
- Ito (2021) [100] describes a facility for cryogenic cavitation on impellers at the University of Tokyo, but there are no subsequent papers and no presence on the web.
- Lack of experimental validation limits the refinement of numerical models, making it difficult to predict cavitation behaviour accurately. Many existing models do not fully account for the thermal interactions that significantly impact bubble dynamics at low temperatures.
- Fundamental research on bubble collapse dynamics and low-temperature experiments is notably absent in the context of cryogenics, further hindering the development of robust and reliable cavitation models.
- Some research has shown that cavitation is less of an issue for cryogenic liquids (Liquid Nitrogen) compared to water. This led to reduced research in this area and therefore the broader implications of cavitation erosion in cryogenics remain largely unexplored.
- Modern experimental facilities are urgently needed to provide key data to enable understanding of pump behaviour in cryogenic hydrogen storage and fuel system.

Fundamental magnetic research gaps include:

- No dedicated research has been found specifically investigating the direct effects of magnetic fields on liquid hydrogen.
- Limited research on modelling impact of magnetic fields on LH2, ID models using commercial software dominate.

Fundamental acoustics research gaps include:

- Only one paper was found to investigate LH2 fluid hammer effects via modelling, with very limited experimental data available to validate this.
- There is only one research institute visible that is investigating Taconis oscillations experimentally (Hyper Lab Washington State University). Given that Taconis oscillations impact heat flux and can impact instrumentation (vibration), these data sets are of key importance.
- Data on the impact airframe vibrations transference to thermoacoustics was not found within the published literature.
- Modelling is predominantly 1D thermoacoustic or uses Method of Characteristics, with only a small number of institutions active in researching in this area.

Fundamental electrical research gaps include:

- Lack of experimental data for accurate model development in flow electrification of LH2 that accounts for various effects like vaporisation, impurities etc.
- Lack of research looking into the application of an electric field on the liquid-vapour surface (EHD) of charged LH2 in aircraft situations.

Fundamental contamination and fluid mixtures research gaps include:

- There is no experimental data on the growth of solid air within liquid hydrogen available within the literature.
- There is limited research on the impact of helium solubility on liquid hydrogen properties.
- There is limited research on the impact of binary mixtures on liquid hydrogen properties.

Fundamental surface and materials interactions research gaps include:

- There is a lack of fundamental research on the interaction with LH2 with materials across the conditions found in a LH2 system. Important effects for thermofluids include wettability, adsorption, permeability, thermal conductivity, and magnetic influence.
- Whilst coatings may provide an effective approach for controlling surface/fluid interaction there are research gaps in knowledge of coating interactions, production methods, material behaviour, temperature resilience, and commercial viability.

Fundamental fluid monitoring, sensing and control:

Areas in which little information on LH2 experimental setup has been found include:

- Transient behaviour quantification, such as understanding multi-phase flow like that which may be seen in a pipe or pumped system.
- Optical techniques to link with transient behaviour, boiling, and multiphase flow.
- Further investigation into novel radio frequency or wider acoustic techniques.
- Sloshing measurement and characterisation, which links with transient behaviour quantification.

Areas in which further development could be beneficial include:

- Use of modern sensing equipment with improved accuracy and repeatability to minimise uncertainty in fundamental LH2 properties.
- Application of methods used for other cryogenic fluids to LH2.
- Use of optics coupled with AI or neural networks to support understanding of multiphase flow, including sloshing.

Experiment design - proxy fluids/scaling research gap:

- Lack of experiments designed to develop and corelate proxy fluids for LH2, i.e. using additives/mixtures of other cryogenic fluids to replicate the properties of LH2.

Modelling Techniques research gaps:

- There are distinct phenomena where a lack of experimental data is impacting the development of modelling tools, these are listed below.

  - Lack of experimental data to provide liquid-surface interface behaviour under dynamic conditions.
  - Lack of experimental data to validate evaporation models, especially under dynamic conditions.
  - Lack of experimental data to validate LH2/GH2 two phase flow in pipelines and within components.
  - Lack of experimental data for supercritical hydrogen and flow behaviour through components and systems.
- Commercial CFD codes are unable to capture experimentally observed ullage compression behaviour.
- Due to the lack of validation data there are sub-models, within both commercial and bespoke simulation tools, that require the setting of a parameter, for which there is no guidance on the value that should be used.

15.2. Scenarios Summary

Scenario reviews were provided to highlight where a lack of fundamental research was impacting component and system level research and development. Each scenario area is listed below with the key research gap impacts.

Refuelling

- Experimental data on the behaviour of refuelling systems and components to provide both simulation validation and insight into the behaviour of the complex flows within refuelling components and systems.
- Development of simulation tools to accurately and robustly capture the complexity of LH2 refuelling components and systems.

Stratification

- Dynamic operational conditions: scenarios such as tank filling, emptying, or rapid pressure changes are not well studied, with most research focusing on static conditions.
- External motion and environmental influences: The effects of external factors like vibration, ambient heating, rotational forces, and varying gravity levels on stratification remain underexplored.
- Non-ideal tank geometries: research has largely concentrated on simplified or standard tank geometries, leaving stratification behaviour in tanks with complex shapes, insulation irregularities, or multiple compartments inadequately investigated.
- Multi-tank systems and large-scale applications: Studies on multi-tank systems and large-scale industrial storage facilities are limited, particularly regarding the interaction of stratification across interconnected tanks.
- Advanced cooling and mixing strategies: Strategies such as active mixing, innovative spray cooling systems, or novel heat exchanger designs remain largely unexplored, despite their potential to disrupt or control stratification effectively.
- Material-specific stratification studies: Limited research exists on how stratification interacts with advanced tank materials, coatings, or insulation systems, particularly under long-term operational conditions.

Pumping

- Materials development optimisation for durability, especially in tribology and sealing.
- Optimisation for efficiency, overall performance, thermal management.
- Optimisation for cavitation control, safety, scalability, and cost-effectiveness.

Chill Down

- Experimental data – there is a fair amount of experimental research; however, it does not appear to cover a wide range of parameters. For example, Hartwig's team has focused on high Reynolds numbers, while a significant portion of studies used liquid nitrogen (LN2) instead of liquid hydrogen (LH2).
- Accurately simulating heat transfer, multiphase flow, phase change, and cavitation in cryogenic conditions. All modelling approaches require assumptions in sub-models or are based on correlations that do not relate to the full range of conditions or are not specific to LH2. Ahuja et al.(2024) [210], obtained accurate results in their numerical models validated against experiments by Hartwig et al.(2020) [209]. However, Ahuja et al [210] concluded that more studies are needed to understand how the annular quench fronts observed in some liquid hydrogen tests evolve.
- Experimental data needs to precisely record boundary conditions, including the behaviour of materials under cryogenic temperatures and the effects of thermal gradients, without this, simulations are based on assumptions which can invalidate the model.

Sloshing

- Experimental data to capture the interaction between turbulence, phase change, and the evolving liquid-vapor interface under dynamic conditions, providing understanding and validation data.
- Experimental data for validating models under a wide range of real-world dynamic conditions, including variations in external conditions, such as vibrations or acceleration, seen for aviation conditions.

Boiloff

- There is a lack of experimental data covering a wider range of parameters required to study boiling process in detail and conditions for aviation.
- This lack of data has impacted numerical modelling development of boil-off.

16. Report References

1. Park, S., et al., Feasibility Study on Production of Slush Hydrogen Based on Liquid and Solid Phase for Long Term Storage. Energies, 2024. **17**(17): p. 4415.
2. Aziz, M., Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety. Energies, 2021. **14**(18): p. 5917.
3. Verfondern. K, Ciccone, D., Mokov, V., Makarov, D., Coldrick, S., Ren, Z., Wen, J., Proust, C., Fridrich, A., Jordan, T., *Handbook of hydrogen safety:Chapter on LH2 safety*. 2021.
4. Jacob W. Leachman, Ø.W., Konstantin I. Matveev, *Cool Fuel - The Science and Engineering of Cryogenic Hydrogen*. 2025: Oxford University Press 2025 ISBN 9780198936664.
5. Fukutani, K. and T. Sugimoto, *Physisorption and ortho–para conversion of molecular hydrogen on solid surfaces.* Progress in Surface Science, 2013. **88**(4): p. 279-348.
6. Jiao, F., et al., *Review of hydrogen ortho–para conversion: experimental data and reaction kinetics.* Reaction Chemistry & Engineering, 2024. **9**(11): p. 2846-2862.
7. Leachman, J.W., et al., *Fundamental Equations of State for Parahydrogen, Normal Hydrogen, and Orthohydrogen.* Journal of Physical and Chemical Reference Data, 2009. **38**(3): p. 721-748.
8. Xu, P., et al., Review of the continuous catalytic ortho-para hydrogen conversion technology for hydrogen liquefaction. International Journal of Hydrogen Energy, 2024. **62**: p. 473-487.
9. da Silva Falcão, B., et al., *Ortho- to para-hydrogen catalytic conversion kinetics.* International Journal of Hydrogen Energy, 2024. **62**: p. 345-351.
10. O'Neill, K.T., et al., *Hydrogen ortho-para conversion: process sensitivities and optimisation.* Chemical Engineering and Processing - Process Intensification, 2023. **184**.
11. Haoren, W., et al., Thermodynamic analysis of the effect of initial ortho-hydrogen concentration on thermal behaviors for liquid hydrogen tanks. International Journal of Hydrogen Energy, 2024. **55**: p. 243-260.
12. Shi, C., et al., Performance analysis of vapor-cooled shield insulation integrated with para-ortho hydrogen conversion for liquid hydrogen tanks. International Journal of Hydrogen Energy, 2023. **48**(8): p. 3078-3090.
13. Teng, J., et al., Comparative study on thermodynamic performance of hydrogen liquefaction processes with various ortho-para hydrogen conversion methods. Energy, 2023. **271**.
14. Zhu, S., et al., Numerical study on comprehensive performance of flow and heat transfer coupled with ortho-para hydrogen conversion. International Journal of Heat and Mass Transfer, 2023. **201**.
15. Zhu, Y., et al., Numerical Study on Thermodynamic Coupling Characteristics of Fluid Sloshing in a Liquid Hydrogen Tank for Heavy-Duty Trucks. Energies (Basel), 2023. **16**(4): p. 1851.
16. Ott, F., et al., Cryostat for the provision of liquid hydrogen with a variable ortho-para ratio for a low-dimensional cold neutron moderator. EPJ Web of Conferences, 2020. **231**.
17. Hannot, Development of a measurement system to measure in-situ the ortho para concentration of liquid hydrogen.pdf>, in 247th ECS Meeting 18-22 May 2025. 2024, IOP Publishing: Canada.

18. Bahrami, J., et al., Effect of orthohydrogen–parahydrogen composition on performance of a proton exchange membrane fuel cell. International Journal of Hydrogen Energy, 2014. **39**(27): p. 14955-14958.
19. Ilisca, E., *Hydrogen Conversion in Nanocages.* Hydrogen, 2021. **2**(2): p. 160-206.
20. Fukutani, K., et al., Photostimulated desorption and ortho-para conversion of H2 on Ag surfaces. Phys Rev Lett, 2003. **90**(9): p. 096103.
21. S.A FitzGerald, H.O.H.C., P. M. Korngut, C. B. Simmons, and Y. E. Strangas, Cryogenic apparatus for diffuse reflection infrared spectroscopy with high=pressure capabilities.pdf>. 2006.
22. Leachman, J.W., et al., *Current Status of Transport Properties of Hydrogen.* International Journal of Thermophysics, 2007. **28**(3): p. 773-795.
23. Sakoda, N., et al., *Review of the Thermodynamic Properties of Hydrogen Based on Existing Equations of State.* International Journal of Thermophysics, 2010. **31**(2): p. 276-296.
24. Ikeuba, A.I., et al., A review on exploring the potential of liquid hydrogen as a fuel for a sustainable future. Sustainable Chemistry One World, 2024. **3**.
25. "Choi, J.W., et al., *Liquid hydrogen properties*. 2004, ; Korea Atomic Energy Research Institute, Taejon (Korea, Republic of): Korea, Republic of. p. Medium: ED; Size: 35 pages.
26. Wang, X., X. Zou, and W. Gao, Flammable gas leakage risk assessment for methanol to hydrogen refueling stations and liquid hydrogen refueling stations. International Journal of Hydrogen Energy, 2024. **54**: p. 1286-1294.
27. Ratnakar, R.R., et al., *Hydrogen supply chain and challenges in large-scale LH2 storage and transportation.* International Journal of Hydrogen Energy, 2021. **46**(47): p. 24149-24168.
28. Dziedzic, W.M., et al., *Analytical comparison of convective heat transfer correlations in supercritical hydrogen*. Journal of Thermophysics and Heat Transfer, 1993. **7**(1): p. 68-73.
29. Locke, J.M. and D.B. Landrum, Study of Heat Transfer Correlations for Supercritical Hydrogen in Regenerative Cooling Channels. Journal of Propulsion and Power, 2008. **24**(1): p. 94-103.
30. D.B, L.J.M.a.L., Uncertainty Analysis of Heat Transfer to Supercritical Hydrogen in Cooling Channels.pdf>, in 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit. 2005: Tucson, Arizona.
31. Pizzarelli, M., *The status of the research on the heat transfer deterioration in supercritical fluids: A review.* International Communications in Heat and Mass Transfer, 2018. **95**: p. 132-138.
32. Ribert, G., D. Taieb, and V. Yang, Large-eddy simulation of a supercritical channel flow using a shock capturing numerical scheme. Computers & Fluids, 2015. **117**: p. 103-113.
33. J.W, H.H.J.a.L., *Critical Temperatures, Pressures, and Volumes ofHydrogen, Deuterium, and Hydrogen Deuteride.* Journal of Research of the National Bureau of Standards, 1951. **47 No. 2**: p. Research Paper 2229.
34. Webeler, R. and F. Bedard, Viscosity Difference Measurements for Normal and Para Liquid Hydrogen Mixtures. The Physics of Fluids, 1961. **4**(1): p. 159-160.
35. Blagoi YP, P.V., *SURFACE TENSION OF HYDROGEN NEAR THE CRITICAL POINT.* Soviet Physics JETP, 1966. **22 (5)**.
36. Briggs, C.K., et al., *Estimated viscosity, surface tension, and density of liquid DT from the triple point to 25 K.* 1975, Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States): United States. p. Medium: ED; Size: Pages: 15.

37. Horie, Y., et al., *Film Boiling Heat Transfer Properties of Liquid Hydrogen in Natural Convection*. PROCEEDINGS OF THE 25TH INTERNATIONAL CRYOGENIC ENGINEERING CONFERENCE AND INTERNATIONAL CRYOGENIC MATERIALS CONFERENCE 2014, 2015. **67**: p. 643-648.

38. Sakoda, N., Shindo, K., Shinzato, K., Kohno, M., Takata, Y., & Fujii, M. , *Review of the Thermodynamic Properties of Hydrogen Based on Existing Equations of State*. International Journal of Thermophysics, 2010. **31(2), 276–296**.

39. Tatsumoto, Y.H.M.S.Y.S.D.H.H.S.H. and Y.N.S.N.H.K.a.Y. Inatani, *Forced flow heat transfer from a round wire in a vertically- mounted pipe to supercritical hydrogen*. IOP Conference Series: Materials Science and Engineering, 2015.

40. Petitpas, G. and S.M. Aceves, *Modeling of sudden hydrogen expansion from cryogenic pressure vessel failure*. International Journal of Hydrogen Energy, 2013. **38**(19): p. 8190-8198.

41. Ganesan, V., et al., Development of Two-Phase Frictional Pressure Gradient Correlation for Saturated Cryogenic Flow Boiling in Uniformly Heated Tubes. International Journal of Heat and Mass Transfer, 2024. **220**: p. 124901.

42. Bellur, K., et al., Results from neutron imaging phase change experiments with LH2 and LCH4. Cryogenics, 2022. **125**: p. 103517.

43. Ahmad, A., E. Oko, and A. Ibhadon, Comparative energy and exergy analysis of ortho-para hydrogen and non-ortho-para hydrogen conversion in hydrogen liquefaction. International Journal of Hydrogen Energy, 2024. **78**: p. 991-1003.

44. Bell I, L.J.W., Rigosi A.F and Hill H. M, Quantum Entropic Effects in the Liquid Viscosities of Hydrogen,Deuterium, and Neon. Physics of Fluids, 2023. **35 (8)**.

45. Beckmueller, R., et al., New Fundamental Equations of State for Binary Hydrogen Mixtures Containing Argon, Helium, and Neon. 2024.

46. Salzano, E., M. Carboni, and G. Pio, *The effects of low-temperature phenomena on rapid phase transition of liquid hydrogen*. International Journal of Hydrogen Energy, 2020. **45**(56): p. 32676-32685.

47. Hu, Z., J. Li, and K. He, *Design and the flow characteristics analysis in an ortho-para hydrogen converter*. International Journal of Hydrogen Energy, 2024. **82**: p. 1314-1323.

48. Sakamoto, Y., et al., Investigation of boiling hydrogen heat transfer characteristics under low-pressure conditions. Cryogenics (Guildford), 2023. **131**: p. 103652.

49. Aso, T., et al., Experimental Investigation of Characteristics of Impinging Jet Heat Transfer and Application to JSNS Moderator Design. Transactions of the Atomic Energy Society of Japan, 2006. **5**(3): p. 179-189.

50. Klaus, M., et al., Conceptual Design of the Liquid Hydrogen Moderator Cooling Circuit for the European Spallation Source. Physics Procedia, 2015. **67**: p. 147-152.

51. Klaus M, E.S., Quack H, Haberstroh C, Bebler Y, *Expansion vessel for supercritical hydrogen in a spallation neutron source moderator circuit*. IOP Conference Series: Materials Science and Engineering, 2015. **101 (1) 012050**.

52. 高田, 保., et al., *高圧水素の熱物性測定*. 水素エネルギーシステム, 2009. **34**(4): p. 4-10.

53. Bartolomeu, R.A.C. and L.F.M. Franco, *Thermophysical properties of supercritical H2 from Molecular Dynamics simulations*. International Journal of Hydrogen Energy, 2020. **45**(33): p. 16372-16380.

54. Assael, M.J., et al., Correlation of the Thermal Conductivity of Normal and Parahydrogen from the Triple Point to 1000 K and up to 100 MPaa). Journal of Physical and Chemical Reference Data, 2011. **40**(3).

55. RW, T.G.a.S., Measurement of liquid and two-phase hydrogen densities with a capacitance density meter, N.A.a.S. Administration., Editor. 1969.
56. Merkle, C.L., et al., *Computation of Flows with Arbitrary Equations of State.* AIAA Journal, 1998. **36**(4): p. 515-521.
57. Choi, J.W., et al., *Liquid hydrogen properties*. 2004: Korea, Republic of.
58. Ohira, K., Development of density and mass flow rate measurement technologies for slush hydrogen. Cryogenics, 2004. **44**(1): p. 59-68.
59. Behnejad, H. and M.S. Miralinaghi, Initial density dependence of the viscosity of hydrogen and a corresponding states expression for high pressures. Journal of Molecular Liquids, 2004. **113**(1): p. 143-148.
60. Diller, D.E., *Measurements of the Viscosity of Parahydrogen.* The Journal of Chemical Physics, 1965. **42**(6): p. 2089-2100.
61. Bell I, L.J.W., Rigosi A.F and Hill H. M, Quantum Entropic Effects in the Liquid Viscosities of Hydrogen, Deuterium, and Neon. Physics of Fluids, 2023. **35 (8)**.
62. Nagashima, H., et al. An Estimation of Thermodynamic and Transport Properties of Cryogenic Hydrogen Using Classical Molecular Simulation. in ASME-JSME-KSME 2011 Joint Fluids Engineering Conference. 2011.
63. Yang, H., et al., Assessment of machine learning models and conventional correlations for predicting heat transfer coefficient of liquid hydrogen during flow boiling. International journal of hydrogen energy, 2024. **49**: p. 753-770.
64. Durbin, D. and C. Malardier-Jugroot, *Review of hydrogen storage techniques for on board vehicle applications.* International Journal of Hydrogen Energy, 2013. **38**: p. 14595-14617.
65. Orlova, S., N. Mezeckis, and V.P.K. Vasudev, *Compression of Hydrogen Gas for Energy Storage: A Review.* Latvian Journal of Physics and Technical Sciences, 2023. **60**(2): p. 4-16.
66. Goncharov, A.F., R.T. Howie, and E. Gregoryanz, *Hydrogen at extreme pressures (Review Article).* Low Temperature Physics, 2013. **39**(5): p. 402-408.
67. Charignon, T., et al., Thermal Conductivity of Subcooled Liquid Hydrogen, in AIP Conference Proceedings. 2008. p. 765-772.
68. Roder, H.M. and D.E. Diller, *Thermal Conductivity of Gaseous and Liquid Hydrogen.* The Journal of Chemical Physics, 1970. **52**(11): p. 5928-5949.
69. Locke, J.M.a.L.D.B., Uncertainty Analysis of Heat Transfer to Supercritical Hydrogen in Cssling Channels. American Institute of Aeronautics and Astronautica, 2005.
70. Weber, M.a., Thermophysical Properties of Parahydrogen from the Freezing Liquid Line to 5000 R for Pressures to 10,000 Psia, C.D. National Institute of Standards and Technology (NIST), Editor. 1972.
71. ER, S.L.a.G., *Thermal Expansion of Liquid Normal Hydrogen Between 18.8 and 22.2 K.* Journal of Research of the National Bureau of Standards, 1984. **89 (4)**.
72. Drube, T.K., et al., Exploring variations in the weight, size and shape of liquid hydrogen tanks for zero-emission fuel-cell vessels. International Journal of Hydrogen Energy, 2024. **80**: p. 1441-1465.
73. Petitpas, G. and S.M. Aceves, *Modeling of sudden hydrogen expansion from cryogenic pressure vessel failure.* International Journal of Hydrogen Energy, 2013. **38**: p. 8190–8198.
74. RJ, C., *Dielectric Constant of Liquid Parahydrogen*, N.I.o.S.a. Technology, Editor. 1962: Gaithersburg, MD.

75. Pashkov, V.V. and M.P. Lobko, *Dielectric Properties of Liquid Hydrogen*, in *Advances in Cryogenic Engineering*, K.D. Timmerhaus and H.A. Snyder, Editors. 1980, Springer US: Boston, MA. p. 709-714.

76. Liu, F.F. and S.W.H. Chow, *Differential dielectric-to-density measurement for cryogenic fluids*. Review of Scientific Instruments, 1987. **58**(10): p. 1917-1925.

77. Hartwig, J., J. Jr, and S. Darr, Parametric Analysis of the Liquid Hydrogen and Nitrogen Bubble Point Pressure for Cryogenic Liquid Acquisition Devices. Cryogenics, 2014. **63**.

78. Hartwig, J., D. Chato, and J. McQuillen, *Screen channel LAD bubble point tests in liquid hydrogen*. International Journal of Hydrogen Energy, 2014. **39**(2): p. 853-861.

79. Zhao, X., J.K. Johnson, and C.E. Rasmussen, *Surface tension of quantum fluids from molecular simulations*. The Journal of Chemical Physics, 2004. **120**(18): p. 8707-8715.

80. Zheng, Y., et al., Effect of microgravity on flow boiling heat transfer of liquid hydrogen in transportation pipes. International journal of hydrogen energy, 2019. **44**(11): p. 5543-5550.

81. Boryaev, A.A., I.O. Chernyaev, and Z. Yuqing, *Heat and mass transfer and hydrodynamics in cryogenic hydrogen fuel systems*. Fuel, 2022. **321**: p. 124004.

82. Bellur, K., et al., *Modeling liquid–vapor phase change experiments: Cryogenic hydrogen and methane*. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2023. **675**: p. 131932.

83. Hartwig, J., et al., A Continuous Flow Boiling Curve in the Heating Configuration Based on New Cryogenic Universal Correlations. Applied Thermal Engineering, 2024. **248**: p. 123235.

84. Mercado, M., N. Wong, and J. Hartwig, Assessment of two-phase heat transfer coefficient and critical heat flux correlations for cryogenic flow boiling in pipe heating experiments. International journal of heat and mass transfer, 2019. **133**: p. 295-315.

85. Ganesan, V., et al., Universal Critical Heat Flux (CHF) Correlations for Cryogenic Flow Boiling in Uniformly Heated Tubes. International Journal of Heat and Mass Transfer, 2021. **166**: p. 120678.

86. LeClair, A., et al., Modeling of cryogenic heated-tube flow boiling experiments of hydrogen and helium with the Generalized Fluid System Simulation Program. Cryogenics, 2024. **143**: p. 103926.

87. Merte, H., Incipient and steady boiling of liquid nitrogen and liquid hydrogen under reduced gravity. 1970.

88. Stochl, R.J., Gaseous-hydrogen Requirements for the Discharge of Liquid Hydrogen from a 1.52 Meter-(5-ft-) Diameter Spherical Tank. 1969: National Aeronautics and Space Administration.

89. Friedman, R., et al., Experimental heat-transfer results for cryogenic hydrogen flowing in tubes at subcritical and supercritical pressures to 800 pounds per square inch absolute. 1966.

90. Shirai, Y., et al., Heat transfer characteristics of liquid hydrogen flowing inside of a vertical heated pipe under quasi-stationary heat input. Cryogenics (Guildford), 2021. **113**: p. 1.

91. Shiotsu, M., et al., Film boiling heat transfer from a wire to upward flow of liquid hydrogen and liquid nitrogen. ADVANCES IN CRYOGENIC ENGINEERING, 2015. **101**(1): p. 12175-12182.

92. Ahmad, F., et al., Saturated nucleate pool boiling of cryogenic fluids: Review of databases, assessment of existing models and correlations, and development of new

universal correlation. International Journal of Heat and Mass Transfer, 2024. **231**: p. 125807.

93. Wang, J., Y. Li, and L. Wang, Numerical Study on Pool Film Boiling of Liquid Hydrogen over Horizontal Cylinders. Energies (Basel), 2022. **15**(3): p. 1044.
94. Fu, W., et al., Study on Convective Heat Transfer Characteristics of Supercritical Liquid Hydrogen in a U-Type Tube inside a Moderator. Energies (Basel), 2022. **15**(10): p. 3605.
95. Li, J. and G. Liang, *Simulation of mass and heat transfer in liquid hydrogen tanks during pressurizing*. Chinese journal of aeronautics, 2019. **32**(9): p. 2068-2084.
96. Qiu, G., et al., Numerical study on unsteady heat transfer and fluid flow in a closed cylinder of reciprocating liquid hydrogen pumps. International journal of hydrogen energy, 2023. **48**(77): p. 30156-30169.
97. Zhang, S., et al., Effect of gravity conditions on heat transfer and flow fluctuations of liquid hydrogen in a non-isothermal horizontal circular tube. International journal of hydrogen energy, 2023. **48**(19): p. 7058-7071.
98. Baldwin, M., et al., Pool boiling in liquid hydrogen, liquid methane and liquid oxygen: A review of available data and predictive tools. Cryogenics (Guildford), 2021. **115**: p. 103240.
99. Baldwin, M., et al., Critical heat flux of liquid hydrogen, liquid methane, and liquid oxygen: a review of available data and predictive tools. IOP conference series. Materials Science and Engineering, 2024. **1301**(1): p. 12165.
100. Ito, Y., The World's First Test Facility That Enables the Experimental Visualization of Cavitation on a Rotating Inducer in Both Cryogenic and Ordinary Fluids. Journal of Fluids Engineering, 2021. **143**(12).
101. Zhu, J., et al., Interactions of vortices, thermal effects and cavitation in liquid hydrogen cavitating flows. International Journal of Hydrogen Energy, 2016. **41**(1): p. 614-631.
102. Yuan, W., et al., Numerical investigation of the leakage and explosion scenarios in China's first liquid hydrogen refueling station. International Journal of Hydrogen Energy, 2022. **47**(43): p. 18786-18798.
103. Hord J, A.L., Hall WJ, *CAVITATION IN LIQUID CRYOGENS CR-2054*, N.A.A.S. ADMINISTRATION, Editor. 1972.
104. Hord J, A., *CAVITATION IN LIQUID CRYOGENS*, N. CR-2242, Editor. 1973, NASA: Cleveland, Ohio.
105. Sun, S., et al., Enhancing Cryogenic Cavitation Prediction Through Incorporating Modified Cavitation and Turbulence Models. Journal of Fluids Engineering, 2021. **143**(6).
106. A, H.A.a.V., *Numerical study of cavitation in cryogenic fluids*. Journal of Fluids Engineering, 2010. **127 (2) 267--281**.
107. Kelly, S., C. Segal, and J. Peugeot, *Simulation of Cryogenics Cavitation*. AIAA Journal, 2011. **49**(11): p. 2502-2510.
108. Huang, R.F.H., R.H., *An experimental study of elevated round jets deflected in a crosswind*. Experimental Thermal and Fluid Science, 2002. **27**(1): p. 77-86.
109. Zhang, S., X. Li, and Z. Zhu, Numerical simulation of cryogenic cavitating flow by an extended transport-based cavitation model with thermal effects. Cryogenics, 2018. **92**: p. 98-104.
110. Dular, M. and M. Petkovšek, *Cavitation erosion in liquid nitrogen*. Wear, 2018. **400-401**: p. 111-118.
111. Ćwik, J., et al., *Layered composite magnetic refrigerants for hydrogen liquefaction*. International Journal of Hydrogen Energy, 2024. **87**: p. 485-494.

112. Feng, T., R. Chen, and R.V. Ihnfeldt, *Modeling of hydrogen liquefaction using magnetocaloric cycles with permanent magnets.* International Journal of Refrigeration, 2020. **119**: p. 238-246.

113. van der Minne, E., et al., The effect of intrinsic magnetic order on electrochemical water splitting. Applied Physics Reviews, 2024. **11**(1).

114. Snadin, A.V., et al., Magnetic field dependence of the para-ortho conversion rate of molecular hydrogen in SABRE experiments. J Magn Reson, 2024. **360**: p. 107630.

115. Hara, S., et al., *Development of Liquid Hydrogen Cooling System for a Rotor of Superconducting Generator.* IEEE Transactions on Applied Superconductivity, 2021. **31**(5): p. 1-5.

116. Shirai, Y., et al., Critical Current Test of Liquid Hydrogen Cooled HTC Superconductors under External Magnetic Field. Physics Procedia, 2016. **81**: p. 158-161.

117. Hirabayashi, H., et al., *Feasibility of Hydrogen Cooled Superconducting Magnets.* IEEE Transactions on Applied Superconductivity, 2006. **16**(2): p. 1435-1438.

118. Hirabayashi, H., et al., *Liquid Hydrogen Cooled Superconducting Magnet and Energy Storage.* IEEE Transactions on Applied Superconductivity, 2008. **18**(2): p. 766-769.

119. Matsumoto, K., et al., *Magnetic refrigerator for hydrogen liquefaction.* Journal of Physics: Conference Series, 2009. **150**(1).

120. Tang, X., et al., Magnetic refrigeration material operating at a full temperature range required for hydrogen liquefaction. Nat Commun, 2022. **13**(1): p. 1817.

121. Zhang, H., et al., Review on the materials and devices for magnetic refrigeration in the temperature range of nitrogen and hydrogen liquefaction. Physica B: Condensed Matter, 2019. **558**: p. 65-73.

122. Walter, H., et al., *Liquid hydrogen tank with cylindrical superconducting bearing for automotive application.* IEEE Transactions on Appiled Superconductivity, 2003. **13**(2): p. 2150-2153.

123. Lighthill, M.J. and M.H.A. Newman, *On sound generated aerodynamically I. General theory.* Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 1952. **211**(1107): p. 564-587.

124. Lighthill, M.J., *The Bakerian Lecture, 1961 Sound generated aerodynamically.* Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, 1962. **267**(1329): p. 147-182.

125. Fahy, F., *Foundations of Engineering Acoustics*. 2000, Southampton: Elsevier.

126. G, S., Thermoacoustics: A unifying Perspective for some engines and refrigerators. 2017: Springer International.

127. Yang Vigor, L.T.C., Combustion Instabilities in Gas Turbine Engines: Operational Experience, Fundamental Mechanisms,and Modeling. Progress in Astronautics and Aeronautics,, 2005. **Volume 210**.

128. Joseph, J., et al., *Fluid-hammer induced pressure oscillations in a cryogenic feed line.* IOP Conference Series Materials Science and Engineering, 2017. **171**: p. 012049.

129. Shenton, M.P., J.W. Leachman, and K.I. Matveev, *Investigating Taconis oscillations in a U-shaped tube with hydrogen and helium.* Cryogenics, 2024. **143**: p. 103940.

130. Shenton, M.P., Matveev KI and Leachman JW, Initiation and suppression of Taconis oscillations in tubes with junctions and variable-diameter tube segments. Materials Science and Engineering, 2024. **1301(1), 12042.**

131. Sun, D., et al., CFD study on Taconis thermoacoustic oscillation with cryogenic hydrogen as working gas. Cryogenics, 2016. **75**: p. 38-46.

132. Taconis, K.W., et al., Measurements Concerning the Vapor-Liquid Equilibrium of Solutions of ${\mathrm{He}}^{3}$ in ${\mathrm{He}}^{4}$ below 2.19\ifmmode^\circ\else\textdegree\fi{}K. Physical Review, 1949. **75**(12): p. 1966-1966.

133. Matveev, K. and J. Leachman, *Combined thermoacoustic cooling and ortho-para conversion of cryogenic hydrogen*. The Journal of the Acoustical Society of America, 2022. **151**: p. A271-A271.

134. Matveev, K.I. and J.W. Leachman, *Thermoacoustic Modeling of Cryogenic Hydrogen*. Energies (Basel), 2024. **17**(12): p. 2884.

135. Chi, J., et al., Study of a gas-liquid-coupled heat-driven room-temperature thermoacoustic refrigerator with different working gases. Energy Conversion and Management, 2021. **246**: p. 114657.

136. Putselyk, S., *Thermal Acoustic Oscillations: Short Review and Countermeasures*. IOP Conference Series: Materials Science and Engineering, 2020. **755**: p. 012080.

137. Gu, Y.F. and K.D. Timmerhaus, Damping criteria for thermal acoustic oscillations in slush and liquid hydrogen systems. Cryogenics, 1992. **32**(2): p. 194-198.

138. Bowen, L., L. Yanzhong, and W. Lei, *Flow electrification characteristics of liquid hydrogen in pipe flow*. International Journal of Hydrogen Energy, 2023. **48**(48): p. 18526-18539.

139. Liu, B., et al., Electrostatic characteristics analysis and risk assessments of liquid hydrogen storage system. International journal of hydrogen energy, 2024. **55**: p. 1322-1334.

140. Liu, B., et al., Investigation on the Electrostatics Saturation of Flow Electrification in the Liquid Hydrogen Transportation. Processes, 2023. **11**(8): p. 2511.

141. Abdurahimov, L.V., et al., *The surface instability of liquid hydrogen and helium*. Low temperature physics (Woodbury, N.Y.), 2012. **38**(11): p. 1013-1025.

142. Brazhnikov, M.Y., et al., *Linear and nonlinear waves on the charged surface of liquid hydrogen*. Low temperature physics (Woodbury, N.Y.), 2001. **27**(9): p. 876-882.

143. Kolmakov, G.V., et al., *Instability and reconstruction of thin liquid layer under inversed gravitation conditions*. Journal of low temperature physics, 2002. **126**(1-2): p. 385-390.

144. Abdurakhimov, L.V., et al., *Two different regimes of the turbulent wave cascade decay on the surface of quantum liquids*. Journal of Physics: Conference Series, 2012. **400**(1): p. 12001-4.

145. Will, J. and C. Haberstroh, *Hydrogen contamination in liquid helium*. IOP Conference Series: Materials Science and Engineering, 2020. **755**: p. 012117.

146. Zheng, X., et al., Numerical simulation of air solidification process in liquid hydrogen with LBM-CA coupled method. International Journal of Hydrogen Energy, 2023. **48**(30): p. 11567-11577.

147. Hammer, M., et al., Classical density functional theory for interfacial properties of hydrogen, helium, deuterium, neon and their mixtures. The Journal of Chemical Physics, 2023. **158**.

148. Richardson, I. and J. Leachman, *Modeling the effects of dissolved helium pressurant on a liquid hydrogen rocket propellant tank*. IOP Conference Series: Materials Science and Engineering, 2017. **278**: p. 012037.

149. K. Cavender, C.E., J. Haney and J. Leachman, . Design of a Helium Vapor Shroud for Liquid Hydrogen Fueling of an Unmanned Aerial Vehicle (UAV)," in Proceedings of the Cryogenic Engineering Conference-CEC,. 2017. Madison,Wisconsin).

150. Lozano-Martín, D., A. Moreau, and C.R. Chamorro, Thermophysical properties of hydrogen mixtures relevant for the development of the hydrogen economy: Review of

available experimental data and thermodynamic models. Renewable Energy, 2022. **198**: p. 1398-1429.

151. Starvin, M., M. Edwin, and K. Kumaresan, Experimental investigation on subcooling of liquid hydrogen by helium gas injection through evacuation. Heat Transfer, 2021. **50**.

152. Liang, W., et al., Numerical Simulation of Erosion Characteristics for Solid-Air Particles in Liquid Hydrogen Elbow Pipe. Sustainability, 2021. **13**: p. 13303.

153. Patil, P., S. Doddagoudar, and P. Hiremath, *Impacts of surface roughness on mixed convection nanofluid flow with liquid hydrogen/nitrogen diffusion*. International Journal of Numerical Methods for Heat & Fluid Flow, 2019. **29**.

154. Hauer, M., et al., A novel design approach: increase in storage and transport efficiency for liquid hydrogen by using a dual concept involving a steel-fiber composite tank and thermal sprayed insulating coatings. Frontiers in Energy Research, 2024. **12**.

155. Good, R.J. and G.V. Ferry, *The Wetting of Solids by Liquid Hydrogen*. Advan. Cryog. Eng., 1963. **Vol: 8**: p. Medium: X; Size: Pages: 306-10.

156. Lei, Y., et al., Internal polymeric coating materials for preventing pipeline hydrogen embrittlement and a theoretical model of hydrogen diffusion through coated steel. International Journal of Hydrogen Energy, 2022. **47**.

157. Dwyer, R.F., G.A. Cook, and O.E. Berwaldt, *The Thermal Conductivity of Solid and Liquid Parahydrogen*. Journal of Chemical & Engineering Data, 1966. **11**(3): p. 351-353.

158. Behruzi, P., et al., Testing an Electrical Capacitance Tomography sensor in liquid hydrogen. 2023.

159. Barrón-Palos, L., et al., *Determination of the parahydrogen fraction in a liquid hydrogen target using energy-dependent slow neutron transmission*. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2011. **659**(1): p. 579-586.

160. Grammer, K., et al., Measurement of the scattering cross section of slow neutrons on liquid parahydrogen from neutron transmission. Physical Review B, 2014. **91**.

161. Xie, Z., et al., Experimental Study on Boiling Vaporization of Liquid Hydrogen in Nonspreading Pool. Processes, 2023. **11**(5): p. 1415.

162. Sakamoto, Y., et al., Investigation of boiling hydrogen flow characteristics under low-pressure conditions - Flow regime transition characteristics. International Journal of Hydrogen Energy, 2021. **46**(11): p. 8239-8252.

163. Nakano, A. and T. Nishizu, Experimental study of liquid level gauge for liquid hydrogen using Helmholtz resonance technique. Cryogenics, 2016. **77**.

164. Filippov, Y.P., A. Filippov, and A. Kovrizhnykh, Diagnostic tools for multiphase flows in cryogenics, LNG-and oil production. 2023. 030001.

165. Chi, J.W.H. and A.M. Vetere. Two-Phase Flow During Transient Boiling of Hydrogen and Determination of Nonequilibrium Vapor Fractions. in Advances in Cryogenic Engineering. 1964. Boston, MA: Springer US.

166. Corruccini, R.J., *Dielectric constant of liquid parahydrogen*. 1962, , National Institute of Standards and Technology, Gaithersburg, MD.

167. Li, X., et al., Measurements of concentration decays in underexpanded jets through rectangular slot nozzles. International journal of hydrogen energy, 2018. **43**(20): p. 9884-9893.

168. Soleimani nia, M., P. Oshkai, and N. Djilali, *Multi-component high aspect ratio turbulent jets issuing from non-planar nozzles*. International journal of hydrogen energy, 2019. **44**(29): p. 15262-15277.

169. Shu, Z., et al., Experimental investigation of hydrogen dispersion characteristics with liquid helium spills in moist air. Process safety and environmental protection, 2022. **162**: p. 923-931.

170. He, Y., et al., Diffusion behavior assessment of underwater active venting for combustible gases: An experimental study with helium instead of hydrogen. International journal of hydrogen energy, 2024. **86**: p. 395-403.

171. Nishizu, T., et al., *Liquid volume measurement for cryogen under microgravity condition*. Microgravity science and technology, 2006. **18**(3-4): p. 190-195.

172. Nakano, A., et al., Liquid volume measurement with a closed Helmholtz resonator under micro-gravity conditions. Cryogenics (Guildford), 2006. **46**(2): p. 126-131.

173. Liu, Z., et al., *Fluid sloshing dynamic performance in a liquid hydrogen tank*. International journal of hydrogen energy, 2019. **44**(26): p. 13885-13894.

174. Wei, G. and J. Zhang, Numerical study of the filling process of a liquid hydrogen storage tank under different sloshing conditions. Processes, 2020. **8**(9): p. 1020.

175. Shu, Z., et al., Diffusion characteristics of liquid hydrogen spills in a crossflow field: Prediction model and experiment. Applied energy, 2022. **323**: p. 119617.

176. Hartwig, J., S. Darr, and A. Asencio, Assessment of existing two phase heat transfer coefficient and critical heat flux correlations for cryogenic flow boiling in pipe quenching experiments. International journal of heat and mass transfer, 2016. **93**: p. 441-463.

177. Hartwig, J.W., E. Rame, and J. McQuillen, Pulse Chilldown Tests of a Tank-to-Tank Liquid Hydrogen Propellant Transfer Line, in 54th AIAA Aerospace Sciences Meeting. 2016.

178. Missey, S., O. Dounia, and L. Selle, *Early-stage flame acceleration in stratified hydrogen-air mixtures: Theory and simulation*. Proceedings of the Combustion Institute, 2024. **40**(1): p. 105279.

179. Kangwanpongpan, T., et al., LES model of flash-boiling and pressure recovery phenomena during release from large-scale pressurised liquid hydrogen storage tank. International Journal of Hydrogen Energy, 2024. **50**: p. 390-405.

180. Indelicato, G., et al., Dataset of Wall-Resolved Large-Eddy Simulations Turbulent Pseudoboiling in Cryogenic Hydrogen Pipe Flows. Journal of Thermophysics and Heat Transfer, 2022. **37**(1): p. 133-146.

181. Perng, Y.-T. *Ansys Blog, "Modeling Liquid Hydrogen Fluid Storage, Filling, and Transportation for a More Sustainable Future",*. 2024; Available from: https://www.ansys.com/en-gb/blog/modeling-liquid-hydrogen-fluid-storage-filling-transportation-more-sustainable-future.

182. Pesich, J., Liquid hydrogen tank chill and no vent fill prediction using CFD., in Cryogenic Engineering Conference. 2023.

183. Mohammadpour, J. and F. Salehi, *A computational analysis of cryogenic hydrogen release under various conditions*. International Journal of Hydrogen Energy, 2024. **56**: p. 676-689.

184. Liang, Y., et al., *Numerical simulation of small-scale unignited hydrogen release*. International Journal of Hydrogen Energy, 2024. **75**: p. 161-170.

185. Cardozo Soares Amaral, P., et al., Risk assessment of hydrogen leakage and explosion in a liquid hydrogen facility using computational analysis. International Journal of Hydrogen Energy, 2024. **91**: p. 950-964.

186. Ustolin, F., et al., *A CFD analysis of liquefied gas vessel explosions*. Process Safety and Environmental Protection, 2022. **159**: p. 61-75.

187. Matveev, K.I. and J.W. Leachman, The Effect of Liquid Hydrogen Tank Size on Self-Pressurization and Constant-Pressure Venting. Hydrogen, 2023. **4**(3): p. 444-455.

188. Matveev, K. and J. Leachman, Modeling of Liquid Hydrogen Tank Cooled with Para-Orthohydrogen Conversion. Hydrogen, 2023. **4**: p. 146-153.

189. Goodwin, D., et al., Cantera: An Object-oriented Software Toolkit for Chemical Kinetics, Thermodynamics, and Transport Processes (2.6.0). 2022.

190. Lv, Z., et al., Real-fluid effects on laminar premixed hydrogen flames under cryogenic and high-pressure conditions. Combustion and flame, 2025. **272**: p. 113837.

191. Ghafri, S., et al., *Modelling of Liquid Hydrogen Boil-Off.* Energies, 2022. **15**: p. 1149.

192. Ehrhart, B.D., E. Hecht, and K. Groth, Hydrogen Risk Assessment Models (HyRAM) (V.3.1) (Technical Reference Manual). 2021: United States.

193. Saini, D., et al., *Improving low-order modelling of cryogenic hydrogen releases.* International Journal of Hydrogen Energy, 2025. **105**: p. 417-426.

194. Thilker, F., A. Tramposch, and F. Giuliani. DESIGN AND SIMULATION MODEL OF A DIRECT SUPPLY CRYOGENIC LH2 FUEL AIRCRAFT SYSTEM FOR AIRBORNE APPLICATIONS. in Proceedings of the ASME Turbo Expo. 2024. American Society of Mechanical Engineers (ASME).

195. Bauer, A., et al., *Energetic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen.* International Journal of Hydrogen Energy, 2019. **44**(13): p. 6795-6812.

196. Genovese, M. and P. Fragiacomo, Hydrogen refueling station: Overview of the technological status and research enhancement. Journal of Energy Storage, 2023. **61**.

197. Mayer, T., et al., Techno-economic evaluation of hydrogen refueling stations with liquid or gaseous stored hydrogen. International Journal of Hydrogen Energy, 2019. **44**(47): p. 25809-25833.

198. Kikukawa, S., H. Mitsuhashi, and A. Miyake, *Risk assessment for liquid hydrogen fueling stations.* International Journal of Hydrogen Energy, 2009. **34**(2): p. 1135-1141.

199. Hoelzen, J., et al., *H2-powered aviation at airports – Design and economics of LH2 refueling systems.* Energy Conversion and Management: X, 2022. **14**: p. 100206.

200. Jurns JM, T.T., Greene WD, Testing of Densified Liquid Hydrogen Stratification in a Scale Model Propellant Tank, NASA, Editor. 2001.

201. Liu, Z., et al., Fluid thermal stratification in a non-isothermal liquid hydrogen tank under sloshing excitation. International journal of hydrogen energy, 2018. **43**(50): p. 22622-22635.

202. Kim, D.-M. and H.J. Lee, Estimation of flammable region through experimental observation of liquid hydrogen cloud leaked under various atmospheric conditions. International Journal of Hydrogen Energy, 2024. **61**: p. 1199-1211.

203. Kritmaitree, P., et al., *Analytical Study of Volumetric Scroll Pump for Liquid Hydrogen Circulating System.* Journal of Nuclear Science and Technology - J NUCL SCI TECHNOL, 2002. **39**: p. 101-107.

204. Ku, A.Y., et al., Liquid pump-enabled hydrogen refueling system for medium and heavy duty fuel cell vehicles: Station design and technoeconomic assessment. International Journal of Hydrogen Energy, 2022. **47**(61): p. 25486-25498.

205. Lai, T., et al., Numerical study on static performance of hydrodynamic bearing in high-speed liquid hydrogen centrifugal pump. International Journal of Hydrogen Energy, 2023. **48**(4): p. 1552-1567.

206. Shao, X. and W. Zhao, Liquid hydrogen centrifugal pump optimization based on reducing hydraulic loss and improving cavitation. International Journal of Hydrogen Energy, 2024. **49**: p. 1419-1431.

207. Rame, E., Flow visualization of liquid hydrogen line chilldown tests, NASA, Editor. 2014.

208. Hartwig, J., et al., *Liquid hydrogen line chilldown experiments at high Reynolds Numbers. Optimal chilldown methods.* International journal of heat and mass transfer, 2019. **137**: p. 703-713.

209. Hartwig, J., et al., *Liquid hydrogen line chilldown experiments at high Reynolds numbers. II. Analysis.* International journal of heat and mass transfer, 2020. **156**: p. 119805.

210. Ahuja, V., et al., Simulations of Cryogenic Line Chilldown with Advanced Sub-Grid Wall Boiling Models. 2024.

211. Banica, M.C. and M.E.N. Wisse, *Dynamical Chilldown Model of a Liquid Hydrogen Feed System.* Journal of Propulsion and Power, 2013. **29**(4): p. 975-981.

212. Umemura, Y., et al., Numerical Simulation on Liquid Hydrogen Chill-down Process of Vertical Pipeline, in AIAA Propulsion and Energy 2019 Forum. 2019.

213. Takeda, D., K. Fukiba, and H. Kobayashi, *Improvement in pipe chilldown process using low thermal conductive layer.* International Journal of Heat and Mass Transfer, 2017. **111**: p. 115-122.

214. RH, F., Large-Scale Liquid Hydrogen Tank Rapid Chill and Fill Testing for the Advanced Shuttle Upper Stage Concept.pdf>, NASA/TP—2013–217482, Editor. 2013.

215. Zhu, S., et al., Efficient cooling strategies for liquid hydrogen pipelines: A comparative analysis. Renewable energy, 2024. **236**: p. 121488.

216. Hauser, D., Kassemi, M, Kartuzova, O, Baker M, Mishic J, MASTERING THE CRYOGENIC FRONTIER: PREDICTING SLOSHING IN CRYOGENIC PROPELLANT TANKS, in 46th Annual AAS Guidance, Navigation and Control (GN&C) Conference. 2024.

217. Himeno, T., et al., Numerical and Experimental Investigation on Sloshing in Rocket Tanks with Damping Devices. Vol. 5. 2007.

218. Takeda, M., et al., Simulation of Liquid Level, Temperature and Pressure Inside a 2000 Liter Liquid Hydrogen Tank During Truck Transportation. Physics Procedia, 2015. **67**: p. 208-214.

219. Jeon, G.-M., S.-M. Jeong, and J.-C. Park, Experimental and numerical investigation of the influences of sloshing motion on the change in boil-off gas/boil-off rate in a cryogenic liquid tank. Ocean Engineering, 2024. **298**: p. 117173.

220. Zuo, Z., et al., A numerical model for liquid–vapor transition in self-pressurized cryogenic containers. Applied Thermal Engineering, 2021. **193**.

221. Hastings, L.J., et al., An overview of NASA efforts on zero boiloff storage of cryogenic propellants. Cryogenics, 2001. **41**: p. 833-839.

222. Haoren, W., et al., Theoretical investigation on heat leakage distribution between vapor and liquid in liquid hydrogen tanks. International Journal of Hydrogen Energy, 2023. **48**(45): p. 17187-17201.

223. Wang, H., et al., Thermal models for self-pressurization prediction of liquid hydrogen tanks: Formulation, validation, assessment, and prospects. Fuel (Guildford), 2024. **365**: p. 131247.

224. Reddi, K., et al., Impact of hydrogen refueling configurations and market parameters on the refueling cost of hydrogen. International Journal of Hydrogen Energy, 2017. **42**(34): p. 21855-21865.

225. Carrere, CFD SIMULATIONS OF THE REFUELING OF LONG HORIZONTAL h2 tanks. 2021.

226. Petitpas, G. and S.M. Aceves, Liquid hydrogen pump performance and durability testing through repeated cryogenic vessel filling to 700 bar. International Journal of Hydrogen Energy, 2018. **43**(39): p. 18403-18420.

227. Hartwig, J., et al., Comparison of cryogenic flow boiling in liquid nitrogen and liquid hydrogen chilldown experiments. International journal of heat and mass transfer, 2015. **88**: p. 662-673.

228. Khurana, T.K., et al., *Thermal stratification in ribbed liquid hydrogen storage tanks*. International Journal of Hydrogen Energy, 2006. **31**(15): p. 2299-2309.

229. Kumar, S.P., et al., Influence of surface evaporation on stratification in liquid hydrogen tanks of different aspect ratios. International Journal of Hydrogen Energy, 2007. **32**(12): p. 1954-1960.

230. Ji, Y., J. Sun, and L. Shi, Numerical Investigation of Convective Heat Transfer to Supercritical Pressure Hydrogen in a Straight Tube. Journal of Nuclear Engineering and Radiation Science, 2018. **4**(3).

231. Samara, H., T.v. Ostrowski, and P. Jaeger, Interfacial and transport properties of supercritical hydrogen and carbon dioxide in unconventional formations. The Journal of Supercritical Fluids, 2024. **205**.

232. Cross, M.F., et al., *Modeling of Chill Down in Cryogenic Transfer Lines*. Journal of Spacecraft and Rockets, 2002. **39**(2): p. 284-289.