Institution of Gas Engineers & Managers

Hydrogen Characteristics and Implications

IGEM Technical Paper
August 2022

About IGEM

The Institution of Gas Engineers & Managers (IGEM) is the UK's Professional Engineering Institution for gas, supporting individuals and businesses working in the global gas industry. IGEM was founded in 1863 with the purpose of advancing the science and relevant knowledge of gas engineering for the benefit of the public.

As a not-for-profit, independent organisation IGEM acts as a trusted source of technical information, guidance and services for the gas sector. In today's net zero context, IGEM is focused on engineering a sustainable gas future–we do this by:

- Helping our members achieve and uphold the highest standards of professional competence to ensure the safety of the public.
- Supporting our members in achieving their career goals by providing high quality products, services and personal and professional development opportunities.
- Acting as the voice of the gas industry when working with stakeholders to develop and improve gas policy.

Key messages of this paper

1. The UK Government analysis estimates that by 2050, 250-460TWh of hydrogen could be needed, making up 20-35 per cent of final energy consumption.
2. A feature of the UK's gas infrastructure is that it provides considerable energy system flexibility, which enables the UK to meet the substantial variations in gas demand throughout the year. Much like natural gas, hydrogen as an energy carrier has the capability of storing large quantities of energy over long periods of time.
3. Energy content per unit volume of hydrogen is around 1/3 that of natural gas (hydrogen has 31% of the energy per unit volume of natural gas).
4. The flammable range at which hydrogen will burn is much wider than methane, 4-75.6 %vol compared to 5-15 %vol and widens with increasing temperature or pressure.
5. Hydrogen is a colourless, odourless and tasteless gas. The type of odorant for hydrogen from recent testing concluded that Odorant NB (used for natural gas) would be a suitable odorant for use in a 100% hydrogen gas grid for combustion applications.
6. Hydrogen is a non-toxic gas. Pure hydrogen does not contain carbon and as such there is no carbon dioxide (CO2) production, nor any carbon monoxide (CO), when hydrogen is burned.
7. Hydrogen embrittlement can occur in metals such as steel, due to the introduction and subsequent diffusion of hydrogen into the metal, causing it to become brittle and fracture.

Policy Context

Following the UK Government's legal commitment to achieve net zero carbon emissions by 2050 and the publication of several high profile strategies starting to chart the UK's course to carbon neutrality, £26 billion of government capital investment has been mobilised for a 'green industrial revolution'[1] .

Net zero is achieved by balancing the amount of greenhouse gases emitted into the atmosphere with the amount removed. Achieving net zero is critical if we are to limit global warming to less than 1.5 degrees by 2100, in accordance with United Nations climate goals and the 2015 Paris Agreement[2], and combat the adverse effects of climate change.

The UK Hydrogen Strategy was published by the Government in August 2021 and outlines the critical role that hydrogen could play in the UK's journey to net zero, supporting decarbonisation efforts across power, industry, heat and transport.

Current and future hydrogen applications

Currently, the UK produces approximately 0.7Mt (27TWh) of hydrogen each year[3], from natural gas without carbon capture. This is almost entirely produced for industrial uses, such as ammonia and fertilizer production, and hydrogenation of oils in petrochemical facilities. To a far lesser extent, hydrogen is used as a fuel for some transport including buses, trucks, cars and marine vessels.

The UK Government has recognised the much wider contribution that hydrogen can make to our net zero targets, committing to a target of 10GW of low carbon hydrogen production capacity by 2030, equivalent to the amount of gas currently consumed by over 6 million households in the UK each year. Potential future applications for hydrogen include the blending and eventual replacement of natural gas in the existing gas network; supporting power generation, and using hydrogen as a fuel to power heavy transport. Government analysis estimates that by 2050, 250-460TWh of hydrogen could be needed, making up 20-35 per cent of UK final energy consumption[4].

The exact balance of future hydrogen demand and end uses is yet to be determined, however, it's potential to support decarbonisation across the wider economy is evident.

1 HM Government, Net Zero Strategy: Build Back Greener, October 2021

2 United Nations Framework Convention on Climate Change

3 National Grid ESO, Future Energy Scenarios, July 2021

4 HM Government, UK Hydrogen Strategy, August 2021

What is hydrogen?

Hydrogen is a chemical element, discovered in 1766 by the English scientist Henry Cavendish. It is the lightest, smallest and most abundant element in the universe and can be found in water and the molecules of nearly all living things. Despite hydrogen's abundance at a molecular level, on Earth its natural form is nearly always found as part of another compound due to its reactive nature, bonded to other elements such as oxygen to form water (H_2O) or with carbon to form methane (CH_4). To isolate its gas form it must be extracted from these compounds[5].

Hydrogen is not an energy source itself, but an energy vector, which means it can effectively carry or store energy. When hydrogen is combusted, it produces only water vapour and no harmful carbon emissions. As such, it represents an alternative to burning fossil fuels, provided the hydrogen is produced using low carbon methods, or where the carbon is captured[6].

The key characteristics of hydrogen gas

The energy, engineering and academic community is continually developing its understanding of how hydrogen behaves under different conditions and how it interacts with its environment. Hydrogen as a fuel has different properties and combustion characteristics compared to hydrocarbon fuels, such as natural gas, comprised mainly of methane. As such the safety and technical risks and implications must be fully understood before hydrogen fuel switching or blending can take place.

As hydrogen has emerged as a viable alternative to natural gas, careful analysis has been conducted to understand the specific differences between hydrogen and methane. The Institution of Gas Engineers & Managers (IGEM), as part of its 'Reference Standard for low pressure hydrogen utilisation'[7] has conducted an extensive review of hydrogen gas characteristics[8], its comparisons to natural gas, the safety implications of its use and its effect on materials. This paper further explains some of the key findings from this work, presenting their implications and identifying pivotal research in the field.

5 Royal Society of Chemistry: Periodic Table Hydrogen Element

6 Imperial College London; Sustainable Gas Institute, A greener gas grid: What are the options?, July 2017

7 The IGEM Reference Standard aims to identify and discuss the principles required for the safety and integrity of Hydrogen installation and utilisation in premises

8 Institution of Gas Engineers & Managers; IGEM/H/1 Reference Standard for low pressure hydrogen utilisation, June 2022

Storability

Much like natural gas, hydrogen as an energy carrier has the capability of storing large quantities of energy over long periods of time. This is possible through a range of storage technologies including physical storage, adsorption and chemical storage[9]. These technologies not only allow for the storage of hydrogen but also for the transportation of hydrogen to where it is needed. Liquid or gaseous forms of hydrogen or hydrogen carriers can be transported by ship, truck or rail, or by using gas pipelines[10].

A feature of the UK's gas infrastructure is that it provides considerable energy system flexibility, which enables the UK to meet the substantial variations in gas demand throughout the year[11]. Given the variability of wind and solar generated electricity, hydrogen's qualities have significant potential benefits to support inter-seasonal storage for periods of peak energy demand e.g. heating homes over the winter months. The scale and duration of energy storage that hydrogen could provide will contribute to a more resilient and efficient future energy system, particularly one that is more reliant on wind and solar for power generation[12].

The UK Government is backing a number of hydrogen storage projects including the pioneering Whitelee green hydrogen project, utilising the UK's largest onshore windfarm near Glasgow and developing the UK's largest electrolyser, to produce hydrogen gas as a way to store energy and provide zero carbon fuel[13].

SSE Thermal and Equinor are developing plans for one of the world's largest hydrogen storage facilities. Upgrading their existing Aldbrough Gas Storage facility in East Yorkshire to store hydrogen; converting the existing caverns or creating new purpose-built caverns to store the low-carbon fuel[14].

Energy density and viscosity

As the lightest known molecule, hydrogen disperses into the air quicker than other gases due to its low molecular mass. The density of hydrogen is eight times smaller than that of methane.

When considering this characteristic for pipeline transportation of hydrogen, it is acknowledged that greater volumetric flow rates would be required to compensate for this density difference. Energy content per unit volume of hydrogen is around 1/3 that of natural gas (hydrogen has 31% of the energy per unit volume of natural gas). However, this does not directly translate to requiring a threefold increase in flow, due to hydrogen flowing far more easily than methane–such that the energy

9 International Journal of Hydrogen Energy, Large-scale storage of hydrogen, March 2019

10 Hydrogen Europe; Gas Infrastructure Europe, How to transport and store hydrogen-Facts and figures, April 2021

11 The Institution of Engineering and Technology; Transitioning to Hydrogen-Assessing the Engineering Risks and Uncertainties, June 2016

12 Energy Networks Association; A System for All Seasons, October 2021

13 UK Government; Press Release–Glasgow to be home to first-of-a-kind hydrogen storage project, November 2021

14 SSE Thermal; Plans for World-Leading Hydrogen Storage Facility at Aldbrough, July 2021

flow rate for hydrogen is 71% that of natural gas[15]. This can be compensated by either: a larger diameter pipeline, an increase in inlet pressure or accepting a larger drop in pressure through the pipeline.

Viscosity is a measure of a gas or liquid's resistance to flow. Hydrogen has a lower viscosity than most gases, including methane, and as it is a small molecule it is prone to leakage through the joints and seals of containers or pipes in which it is being stored or transported. There are however, methods of detecting hydrogen leaks using sensors linked to local or centralised alarm systems. These types of sensors are already used in industry to successfully detect hydrogen leaks[16].

The H21 Phase 1 project led by Northern Gas Networks, with the support of HSE Science Division and DNV, investigated the critical safety evidence on leakage and consequences of leakage within a 100% hydrogen distribution network. They evidenced that assets that were gas tight on methane were also gas tight on hydrogen, and assets that leaked on hydrogen also leaked on methane-All of the repairs that sealed methane leaks were also effective when tested with hydrogen[17]. There is further ongoing study underway to fully understand and manage all the risks associated with 100% hydrogen in the UK gas network, however, these early conclusions show promise.

In the event of hydrogen leakage, its low density and high diffusivity can be advantageous from a safety perspective. Hydrogen leaks are likely to quickly disperse into the air, providing it is not near an ignition source. This characteristic is an advantage for outdoor hydrogen systems because leaks will be rapidly dispersed. In enclosed spaces, leaking hydrogen will accumulate, potentially creating an explosive mixture. This is a crucial consideration for the design of ventilation systems in enclosed spaces.

Ignition and flammability

Like many gases, hydrogen is flammable. The flammable range at which hydrogen will burn is much wider than methane, 4–75.6 %vol compared to 5–15 %vol and widens with increasing temperature or pressure.

The minimum ignition energy of hydrogen is 0.02mJ, significantly lower than methane at 0.29mJ. This means that it takes much less energy to trigger the ignition of hydrogen than it does for methane and there are various potential sources of ignition including electrical, mechanical and thermal, that pose ignition risks.

The peak burning velocity of hydrogen is around eight times greater than methane. This characteristic links to flame stability and is an important consideration for burners in appliance and combustion equipment.

15 Element Energy; Hydrogen supply chain evidence base, November 2018

16 Rigas F. and Amyotte P.R., 2013, Myths and Facts about Hydrogen Hazards, Chemical Engineering Transactions, 31, 913-918 DOI: 10.3303/CET1331153

17 H21; Phase 1 Technical Executive Summary, May 2011

Hydrogen's greater burning velocity can also lead to increased risk of flashback and damage to some gas appliances, if combustion velocity is larger than the flow velocity[18].

The combined characteristics of higher burning velocity, lower ignition temperature and wider flammable range may lead to easy and undesired combustion if hydrogen gas leaks. However, whether the hydrogen ignites and detonates will depend on various important factors such as the level of hydrogen concentration, leakage conditions, room ventilation, and proximity to ignition sources.

As part of the HyTechnical project, IGEM is reviewing its IGEM/SR/25 - *Technical Standard for hazardous area classification of natural gas installations*, developing a new version of the Standard specific to hydrogen which will address considerations such as release environments, enclosed spaces, ventilation and zoning.

Visibility and odour

Hydrogen is a colourless, odourless and tasteless gas, which are characteristics that have serious implications for leak detection and public safety.

Natural gas in its pure form is also colourless and odourless. Natural gas's lack of odour has been mitigated by the addition of a harmless chemical called Odorant NB (a mixture of t-butyl mercaptan (TBM) and dimethyl sulphide (DMS)), to provide its distinctive smell and alert consumers to leaks.

It will be critical that an odour is added to any pipeline distributed hydrogen, to ensure leaks are detected and consumers are protected. The type of odorant for hydrogen has not yet been formally agreed, however recent testing concluded that Odorant NB (used for natural gas) would be a suitable odorant for use in a 100% hydrogen gas grid for combustion applications[19].

The H21 project, led by Northern Gas Networks is utilising a disused network of gas mains to test operational procedures under 100% hydrogen conditions, installing a dual pump system to odorise hydrogen in the same way that natural gas is odorised today[20].

Flame visibility is an important safety feature. Hydrogen burns with a less visible flame than natural gas and can often be difficult to see. Testing undertaken by SGN (specific to their H100 Fife network) concluded that hydrogen flames are likely to be clearly visible for releases above 2 bar, however at lower pressures hydrogen flame visibility is dependent on factors such as background colour and ambient lighting-where the hydrogen flame is most visible under low ambient lighting, against a dark background, and least visible under high ambient lighting against a light background[21].

18 THyGA; Impact of Hydrogen Admixture on Combustion Processes–Part II: Practice, December 2020

19 SGN; Hydrogen Odorant and Leak Detection Part 1, Hydrogen Odorant Project Closure Report, November 2020

20 H21 News; Hydrogen to smell like natural gas for the first time, November 2021

21 SGN; Flame Visibility Risk Assessment 10172283-1, February 2021

Recent research by the Hy4Heat project, determining if there is a requirement for adding a colourant to hydrogen, concluded that a colourant is not required as it does not offer significant additional benefit in relation to safety when compared to natural gas, and may adversely impact health and appliance operation[22]. Manufacturers of domestic hydrogen gas appliances in Work Package 4 of the project have developed designs to overcome the flame visibility issue without the need for a centrally added colourant.

Toxicity

Hydrogen is a non-toxic gas. Pure hydrogen does not contain carbon and as such there is no carbon dioxide (CO2) production, nor any carbon monoxide (CO), when hydrogen is burned[23]. As well as clear benefits for the environment, burning hydrogen does not carry the same risk to consumers of carbon monoxide poisoning compared to fossil gas.

With regard to concerns over production of nitrogen oxides (NOx) caused by the higher flame temperatures of hydrogen, evidence is pointing to significantly reduced NOx emissions from hydrogen boilers, compared to the most modern natural gas boilers on the market today[24], although this may not be the case for some larger industrial and commercial applications. However, the Hy4Heat project also reports that evolving research is demonstrating that engineering options can be applied to reduce NOx emissions, compared to the equivalent natural gas burning equipment.

Effect on materials

Hydrogen is non-corrosive in standard conditions, however, it can compromise the strength of some materials. Hydrogen embrittlement can occur in metals such as steel, due to the introduction and subsequent diffusion of hydrogen into the metal, causing it to become brittle and fracture. The ability of hydrogen to degrade materials is dependent on several factors including operating pressure, temperature, hydrogen concentration, contaminants, material, microstructure, the nature of a crack front, plastic strain and residual stresses within the material.

As a result of embrittlement, the storage or transport mechanism for hydrogen could experience reduced ductility and load bearing capacity, increasing the risk of fracture and the leakage of hydrogen into the air, making it flammable.

Following an extensive review, IGEM's Reference Standard for low pressure hydrogen utilisation[23] presents the effects of hydrogen on a variety of materials including metals, polymers and elastomers. The Standard identifies a number of gaps in materials that require further study, to fully understand the impact of long-term exposure to 100% hydrogen.

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22 Hy4Heat; Hydrogen Colourant Report, May 2021

23 Institution of Gas Engineers & Managers; IGEM/H/1 Reference Standard for low pressure hydrogen utilisation, June 2022

24 Gersen, S. Darmeveil, H. Van Essen, M. Martinus, G.H. and Teerlingc, O.J, Domestic hydrogen boilers in practice: enabling the use of hydrogen in the built environment, March 2020

The THyGA project[25] is working to understand the consequences of injecting hydrogen into gas distribution networks from a material compatibility perspective. Their study[26] focuses on the non-combustion related aspects of injecting hydrogen in the gas distribution networks within buildings. This includes hydrogen embrittlement of metallic materials and its chemical compatibility with other materials.

ThyGA presents results that show the least susceptible materials to hydrogen embrittlement are low alloy steels, followed by stainless steels, aluminium, copper and brass alloys. They conclude that the relative low pressures of a gas distribution network (between 30-50mbar) means that a gas mixture of natural gas and up to 50% hydrogen should not cause embrittlement issues for the metals used in the network. This supports the drive towards hydrogen blending (up to 20%) into the existing gas network, to make early carbon emissions savings. They also report that polyethylene (PE) was found to have "no corrosion issues and no deterioration or ageing was observed after long term testing in hydrogen gas"- this supports previous studies providing assurance that the programme of work replacing aging iron pipes with PE pipes will support the UK gas network in being hydrogen ready.

Our understanding of hydrogen's characteristics and behaviours will continue to evolve through further research and collaboration across industry, academia and government agencies. There are still important gaps in understanding, which must be addressed before the widespread adoption of hydrogen across the gas network. IGEM will continue to support the technical development work and evidence gathering needs of industry and policy makers.

Visit the IGEM website for information on our areas of work and details of how IGEM Membership can help you stay informed on hydrogen developments, grow your professional network and support your professional development.

If you would like access to IGEM's extensive digital library of hydrogen research, technical reports, videos and other useful resources, please visit our Hydrogen Knowledge Centre for more information.

25 THyGa Project EU: Testing Hydrogen admixture for Gas Applications

26 THyGA; Testing Hydrogen admixture for Gas Applications: Non-combustion related impact of hydrogen admixture-material compatibility, June 2020

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