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Review

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State of the art and knowledge gaps in gaseous hydrogen pipelines, from the perspective of materials, design, and integrity management

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Abstract: Widespread use of green hydrogen is a critical route to achieving a carbon-neutral society, but it cannot be accomplished without extensive hydrogen distribution. Hydrogen pipelines are the most energy-efficient approach to transporting hydrogen in areas with high, long-term demand for hydrogen. A well-known fact is that the properties of hydrogen differ from those of natural gas, which leads to significant variations in the pipeline transportation process. In addition, hydrogen can degrade the mechanical properties of steels, thereby affecting pipeline integrity. This situation has led to two inevitable key challenges in the current development of hydrogen-pipeline technology: economic viability and safety. On the basis of a review of the current state of hydrogen pipelines in terms of material compatibility with hydrogen, design methods, process operations, safety monitoring, and standards, this paper focuses on the following knowledge gaps in gaseous hydrogen pipelines: utilisation of high-strength materials for hydrogen pipelines, design of high-quality hydrogen pipelines, determination of hydrogen velocity, and repurposing of existing natural-gas pipelines. This review aims to identify the challenges in current hydrogen pipelines development and provide valuable suggestions for future research.

Key words: Hydrogen pipelines; Hydrogen embrittlement; Standards; Pipeline design; Hydrogen velocity

1 Introduction

Hydrogen energy is poised to play a significant part in the expected global energy transformation and the construction of a new energy system. It serves as a crucial energy carrier for achieving a carbon-neutral society (Ishaq and Dincer 2020; Kovač et al. 2021). According to the prediction of the Energy Transition Commission (Lord Adair Turner et al. 2021), direct electrification through renewable energy will account for 68% of the global energy demand in 2050. However, the use of renewable energy sources poses two major challenges. Firstly, wind, photovoltaic (PV), and hydroelectric power have intermittent and fluctuating characteristics. Secondly, achieving large-scale and long-term storage is difficult (Ozturk and Dincer 2021). Hydrogen derived from renewable energy sources has the potential to address the aforementioned challenges while facilitating energy security, enhancing resilience, and delivering economic value and environmental advantages for various applications in several sectors. Hydrogen demand is anticipated to constitute around 13% of the total energy demand as a terminal energy source by 2050 (Lord Adair Turner et al. 2021). In 2020, approximately 90 Mt of hydrogen were produced globally, with coal remaining a significant source of hydrogen production. However, less than 1% of this was produced via low-carbon methods. Meanwhile, hydrogen production through water electrolysis made up only 0.03% of the total output. Global hydrogen demand is expected to reach 660 Mt by 2050, and green hydrogen will dominate the market (Wappler et al. 2022). With the advancement of technology and the development of the hydrogen energy sector, the cost of producing green hydrogen from renewable energy sources will gradually decrease, resulting in a considerable amount of hydrogen transport (Julien Armijo et al. 2022).

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Four main methods are used for large-scale hydrogen delivery: gaseous tube trailers, liquid tankers, gaseous hydrogen pipelines and chemical hydrogen carriers (Herib Blanco et al. 2019; Moradi and Groth 2019). In contrast to other methods, pipelines can satisfy the following requirements concurrently: large scale (thousands of tonnes/day), long distance (thousands of kilometres), and long duration (15–30 years) (Lord Adair Turner et al. 2021; Julien Armijo et al. 2022). Although construction of hydrogen pipelines requires significant capital investment, they offer a lower operational cost over time when hydrogen demand is high. There are two methods of transporting hydrogen via pipelines: building new pipelines for pure hydrogen transport or repurposing existing natural-gas pipelines to transport blended or pure hydrogen.

Over the past few years, an increasing number of countries (more than 30) have recognised the irreplaceable role of hydrogen pipelines in the development of the hydrogen energy industry (Agarwal 2022). Consequently, they have begun to plan for the construction of hydrogen pipelines.

By 2017, the United States had more than 2,500 km of hydrogen transmission pipelines, mostly located on the Gulf Coast due to the significant demand for hydrogen in petroleum refineries (Neha Rustagi and Herie Soto 2017). The federal government has funded research and development related to hydrogen pipelines since the 1960s, supported by the National Aeronautics and Space Administration (NASA), the United States Department of Energy, the United States Department of Transportation, and the National Institute of Standards and Technology (NIST). Their research focuses on materials science, hydrogen-pipeline safety, pipeline economics, hydrogen markets, and pipeline network modelling, among other topics (Parfomak 2021).

To accelerate the decarbonisation process, Europe launched the RepowerEU plan in 2022. According to the plan, Europe will build new hydrogen pipelines and repurpose existing natural gas pipelines. The Europe Hydrogen Backbone (Rik Van Rossum et al. 2022) project aims to build five hydrogen corridors by 2030, connecting hydrogen production and consumption sites. By 2040, 53,000 km of hydrogen pipelines will be built, of which 40% will be new pipelines and the remaining 60% will be converted from existing natural gas pipelines.

At present, approximately 100 km of hydrogen pipelines are in operation in China (Wang et al. 2022). The number of projects related to hydrogen and blended-hydrogen pipelines has rapidly increased in recent years. According to the Blue Book on China Hydrogen Energy Industry Infrastructure Development (2016), China plans to build more than 3,000 km of hydrogen pipelines by 2030. Because of the uneven geographical distribution of renewable energy sources, the overall layout involves transporting hydrogen from the western part of China to the eastern part, and hydrogen from the sea to land.

Co-development of blended-hydrogen and pure-hydrogen pipelines is an important component of future hydrogen-pipeline layouts. However, there are quite a few obstacles to construction of hydrogen pipelines and repurposing of existing natural gas pipelines. Hydrogen leaks easily, is flammable (ignition energy = 0.017 mJ) and explosive (explosion range = 18%–59%), and causes degradation of the mechanical properties of steel (Ball and Wietschel 2009; Agarwal 2022). The experience gained from constructing natural-gas pipelines has great importance for hydrogen pipelines. However, initial identification of the distinctions between hydrogen pipelines and natural-gas pipelines is crucial. This paper summarises these distinctions in two main points.

Firstly, hydrogen causes a degradation of the mechanical properties of some materials (Wang et al. 2022). This impact must be assessed when designing pipelines (Guy et al. 2021). Adjustments to design methods or a decrease in pipeline operating pressure may be required. Moreover, defects form continuously during pipeline construction and operation, and hydrogen reduces the ability of steel to resist fracture. Hence, periodic inspection and integrity assessment of hydrogen pipelines must be carried out, and these require certain modifications (Boukortt et al. 2018).

Secondly, the physical properties of hydrogen are significantly different from those of natural gas (Zheng et al. 2010). Given hydrogen's lower volumetric calorific value relative to natural gas, (approximately one third), its energy-transport efficiency is diminished at equivalent volumetric flow rates. Consequently, certain operating parameters of hydrogen pipelines, such as velocity and pressure, may require adjustment to optimize performance. In addition, given variations in the gas's physical properties (e.g., density, viscosity, compression ratio), further analysis is required to determine the applicability of some equipment, such as valves and compressors.

This review provides an overview of the state of the art and knowledge gaps in the field of gaseous hydrogen pipelines, with the aim of highlighting the challenges that currently impede their development. More specifically, we discuss five aspects: (1) hydrogen compatibility with metallic materials in hydrogen pipelines; (2) design methods for hydrogen pipelines; (3) limitation of hydrogen-flow velocity in pipelines; (4) integrity assessment of hydrogen pipelines and in-line inspection; and (5) conversion services for natural gas pipelines.

2 Hydrogen compatibility of material

2.1 Pipeline material

Currently, the generally accepted international standard for steel pipeline materials is API SPEC 5L ‘Specification for Line Pipe’, published by the American Petroleum Institute. X42, X46, and X52 were first included in API 5L in 1947, marking a transition from low-carbon steel to high-strength low-alloy steel in pipeline construction. With the implementation of microalloying and thermo-mechanical controlled process technologies, pipeline steel strength and toughness have improved significantly. The early pipeline steels, primarily composed of ferrite-pearlite, have evolved towards modern high-strength pipeline steels characterized by the presence of acicular ferrite and granular bainite.

Table 1 shows the materials, design pressure, diameter, and wall thickness used in some natural-gas and hydrogen pipelines. A major trend in pipeline technology is to increase the pressure and diameter, which can be achieved by increasing the strength of the material and the normal thickness of pipelines. This approach can significantly reduce the capital for and operating costs of a pipeline, and studies have shown that each grade increase in the strength of a pipeline can reduce costs by 5% to 15% (Fekete et al. 2015). Currently, X70 and X80 are generally used in natural-gas pipelines. However, hydrogen pipelines commonly use relatively low-strength materials (such as X42 and X52), resulting in low transport efficiency and high construction costs. As the amount of hydrogen continues to rise, the need for high-pressure, large-diameter pipelines increases. Hydrogen embrittlement (HE) is an unavoidable problem in high-pressure hydrogen environments such as hydrogen pipelines. It is particularly pronounced in high-strength steels due to the accumulation of significant elastic strain prior to plastic deformation. As a result, the stress required for crack propagation is reduced. The current standard for hydrogen pipelines (ASME B31.12) imposes some limitations on the use of high-strength steels to prevent pipeline failure due to HE in high-strength steels.

Table 1 Comparison of materials, diameters, and pressures of hydrogen and natural gas pipelines (Minato et al. 2012; Huo et al. 2016; Wang et al. 2022)

	Pipeline Name	Material	Thickness (mm)	Pressure (MPa)	Diameter (mm)
Natural gas pipelines	Bovanenkovo-Ukhta	X80	23, 27.7, 33.4	11.8	1420
	West-to-East Gas Transmission Line 1	X70	14.6	10	1016
	West-to-East Gas Transmission Line 2	X80	18.4	12	1219
	Nord Stream pipeline	X70	26.8–41	22–10.6	1220, 1153
	China-Russia Eastern Pipeline	X80	21.6	12	1422
Hydrogen pipeline	Jiyuan-Luoyang	L245 (equals API 5L grade B)	11.1, 11.9	4	508
	Texas Hydrogen Pipeline	X42	/	3–4	273
	SNAM 440 km (planning)	X60	11.1, 15.9	/	660

2.2 HE of pipeline steel

The mechanical properties of metal used in hydrogen environments for long periods of time are degraded by hydrogen, a phenomenon known as environmental HE. Hydrogen molecules can easily adsorb on the metal surface, thereby dissociating into hydrogen atoms, and finally enter the bulk metal (Li et al. 2022). Hydrogen atoms can diffuse in the metal lattice and aggregate at stress concentration regions (such as crack tips) and hydrogen traps (dislocations, grain boundaries, phase boundaries, etc.), thereby deteriorating the mechanical properties of materials and increasing the risk of pipeline failure (Hoschke et al. 2023). Despite a century of study, no definitive consensus has been reached on the precise mechanism of HE. At present, the primary theories on HE include hydrogen-enhanced localised plasticity, hydrogen-enhanced decohesion, hydrogen-enhanced strain-induced vacancy formation, hydrogen pressure theory, and the synergistic effects of multiple mechanisms that contribute to degradation of steel performance in a hydrogen environment (Djukic et al. 2019; Wu et al. 2022).

Mechanical tests in high-pressure hydrogen environments are usually used to quantify the degradation effect of hydrogen on steel performance, and the test results can be directly implemented in pipeline construction. The tests mainly focus on slow strain rate tensile, fatigue crack growth rate (FCGR), and fracture toughness. The primary standards used to assess HE sensitivity of metals are ASTM G142-98, ANSI/CAS CHMC-1, and GB 34542.2.

Numerous studies indicate the following mechanical properties of pipeline steel in hydrogen environments:

1. Hydrogen has little effect on the yield and tensile strength of pipeline steel, but mitigates elongation and reduction in the area (Capelle et al. 2011; Slifka et al. 2014; Cheng and Chen 2017).
2. Hydrogen can significantly decrease the ability of a material to resist crack propagation (Wang et al. 2022). The FCGR at high ΔK will be significantly increased, and the fracture toughness and threshold stress intensity factor will decrease even at a very low hydrogen concentration (Wang 2009).

It is commonly accepted that the behaviour of steels in hydrogen environments is influenced by material attributes, environment, and stress levels (Laureys et al. 2022; Wang et al. 2022). The impact of manufacturing processes on HE of steels is frequently disregarded. In fact, however, manufacturing quality plays a critical role in ensuring the reliability of structural components in a hydrogen environment. This article presents these considerations in four sections, as illustrated in Fig. 1.

1. Material: Extensive research (Nanninga et al. 2012) suggests that high-strength pipeline steel is more vulnerable to HE. Microstructures with higher hardness, such as martensite and bainite, are more susceptible to HE than softer microstructures such as ferrite. In addition, the concentration of hydrogen traps in the steel significantly affects its susceptibility to HE. Hydrogen trapped in irreversible traps, such as second-phase particles/precipitates, is less detrimental to HE (Bhadeshia 2016). Therefore, intro-

ducing irreversible hydrogen trapping sites into materials is an effective approach to suppressing internal hydrogen migration and alleviating HE (Sun et al. 2023). Impurity elements and their inclusions are unavoidably incorporated into materials during the smelting process. Hydrogen is prone to accumulating at the tips of the inclusions, whereby these inclusions can generate lattice distortion, causing stress concentration and ultimately prompting hydrogen atom diffusion (Xue and Cheng 2011; Mostafijur Rahman et al. 2019). This makes inclusions an easy starting point for hydrogen-induced fracture (Huang et al. 2010). However, controlling the size, shape, and distribution of inclusions also enables them to be used as hydrogen traps to reduce the HE susceptibility of materials (Sun et al. 2021). It is worth noting that grain boundaries act as reversible hydrogen traps, with experimental evidence indicating their role as preferential hydrogen diffusion pathways and potential sites for damage initiation (Thomas and Szpunar 2020; Jack et al. 2020). However, HE of materials can be mitigated by grain refinement, due to the fact that an increase in grain boundaries results in a lower hydrogen concentration per unit of grain boundary surface (Ferreira et al. 1998; Haq et al. 2013; Zhou et al. 2019b).

2. Manufacture: The manufacturing process of pipelines also has a significant influence on hydrogen embrittlement. Materials undergo a series of manufacturing processes, such as forming (Wu et al. 2021a; Wu et al. 2021b), welding (Hoschke et al. 2023), and heat treatment. The microstructure of the material is inevitably affected by manufacturing, changing its susceptibility to HE. For instance, plastic deformation at room temperature leads to an increase in dislocation density (Zhou et al. 2019a), which increases the number of hydrogen trapping sites. This slows down hydrogen diffusion and increases the HE susceptibility of the material (Michler et al. 2015; Qu et al. 2019; Han et al. 2019). However, as dislocation density continues to rise, dislocation cell walls begin to form. The proliferation of these walls reduces HE susceptibility, which is attributable to the strong hydrogen trapping capacity of the dislocation cell walls' central structure; this structure forms irreversible hydrogen traps (Chen et al. 2020). Han et al. (2019) discovered that with an increase in pre-strain, the hydrogen diffusion coefficient of X100 pipeline steel decreased, but HE sensitivity increased. Bending procedures are essential in the process of laying pipelines. The two primary methods involved are cold bending and hot bending. A study conducted by Salzgitter AG (Golisch et al. 2022) demonstrated that hot-induction-bent pipes have better hydrogen compatibility than those bent cold. Notably, cold bending results in a significant amount of plastic deformation in a pipeline, which may increase its HE susceptibility (Zvirko 2022). Controlling the microstructure and stress distribution of the material by heat treatment can create a balance between the mechanical properties and HE resistance (Krishnan and Raja 2019; Tan et al. 2022). Welding, an indispensable process in pipeline manufacturing, has a multifaceted impact on the HE sensitivity of a material. Detailed explanations on this topic will be provided later in this paper.

3. Stress: The sensitivity of a material to HE is directly linked to the magnitude of stress it experiences. S–N curves indicate a significant reduction in fatigue life for low cycle fatigue when a material is exposed to hydrogen gas, but fatigue life is hardly reduced in the case of high cycle fatigue (Gilgert et al. 2009; An et al. 2017). In addition, the FCGR curve exhibits a similar trend, in which the acceleration of FCG by hydrogen is not significant at lower values of ΔK (Drexler et al. 2014). Furthermore, stress affects the process of hydrogen adsorption on the material surface. Xu et al. (2022) revealed that tensile stress heightened both the surface energy and activity of hydrogen adsorption sites on the surface of X70 pipeline steel, resulting in a rise in hydrogen atom concentration on the subsurface and thus increasing the susceptibility of the steel to HE.

4. Environment: As hydrogen pressure increases, the HE of a material becomes more serious (Nanninga et al. 2012). According to Sievert’s law, the concentration of hydrogen follows a proportional relationship with the square root of hydrogen fugacity, which means that a high hydrogen pressure corresponds to a high concentration of hydrogen in the material. Consequently, increasing hydrogen pressure can promote FCGR and make the material more susceptible to brittle fracture (Zhang et al. 2021). Shang et al. (2023) showed that increasing the total gas pressure amplified the HE sensitivity of GB 20-grade steel (20#) while keeping the hydrogen partial pressure constant. This phenomenon is

attributable to the increase in total gas pressure, which causes hydrogen molecules to enter the potential field of the iron surface earlier, thereby accelerating hydrogen dissociation. As temperature rises, the bulk hydrogen concentration in the material increases (Xing et al. 2019). However, studies suggest that the HE sensitivity of pipeline steels does not increase monotonically with temperature. Instead, the most significant HE occurs at room temperature (K.Xu and Praxair 2012). Xing et al. (2021) suggest that as the temperature increases, the number of hydrogen atoms saturated in the plastic zone at the crack tip (N) and the rate at which hydrogen moves to the crack tip (V) tend to rise. Meanwhile, the hydrogen saturation time at the crack tip (T = N/V) illustrates a tendency to increase and then eventually decrease as the temperature changes. At room temperature, the hydrogen atoms situated at the tip of the crack have the shortest saturation time, suggesting higher susceptibility to HE.

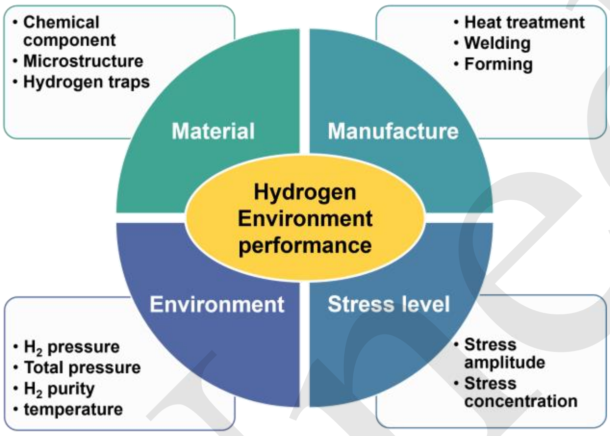

Fig. 1 Factors affecting mechanical properties of steel in hydrogen environments

2.3 Knowledge gaps in hydrogen compatibility of material

2.3.1 Impact of gas impurities on HE

Numerous mechanical tests are typically conducted to evaluate a material's susceptibility to HE. However, most of these tests are carried out in an atmosphere of air, pure hydrogen, or a hydrogen/inert gas mixture, without taking into account the impact of gas impurities on HE subsequent to the blending of hydrogen with natural gas. As shown in Fig. 2(a), Shang et al. (2020a) found that CO_2 in natural gas further accelerates the FCGR of 20# in hydrogen-blended natural gas. Through EBSD analysis of fatigue fracture paths, limited deformation activity was observed around the crack in KAM maps during testing in a hydrogen environment. This phenomenon was more pronounced in the presence of CO_2. Subsequently, Zhou et al. (2022) further investigated the mechanism by which CO_2 enhances HE through gaseous hydrogen permeability tests. The test results show that CO_2 reduces hydrogen penetration time in pure iron. First-principles calculations indicate that CO_2 reduces the energy barrier for H diffusing from the surface to the sub-surface. As a result, hydrogen atoms diffuse to the sub-surface faster, thus increasing the hydrogen concentration at the crack tip.

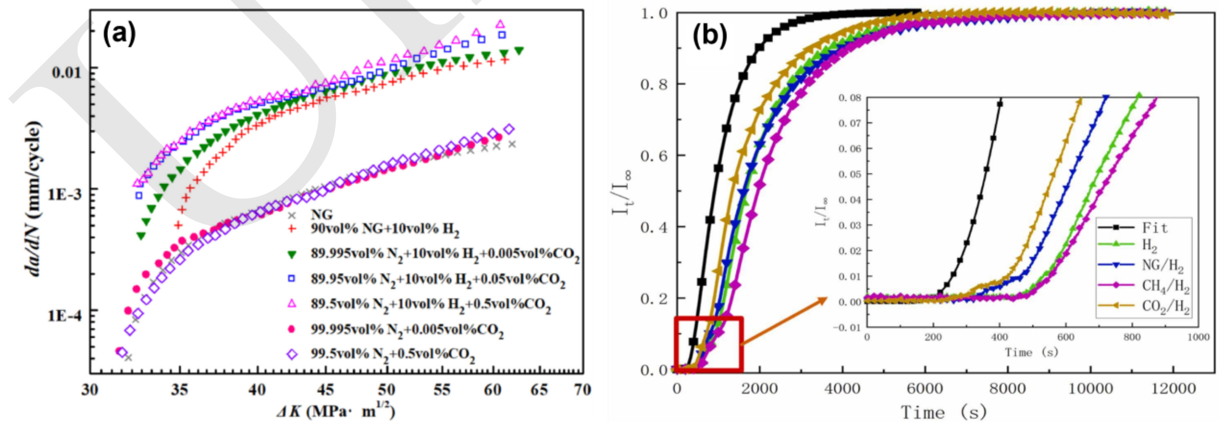

Fig. 2 Enhancement effect of CO2 on HE. (a) FCGR tests (b) gaseous hydrogen permeation tests in H2 and H2/CO2 environments (Shang et al. 2020a; Zhou et al. 2022)

Earlier research showed that in addition to CO_2, H_2S can also enhance HE. However, some impurity components in natural gas can impede HE (Michler et al. 2012; Kotu et al. 2022), such as SO_2, CO, and O_2. The process of adsorption, dissociation, and absorption of hydrogen on metal surfaces in the presence of impure gas can be assessed by molecular simulation. Xing et al. (2023) discovered through first-principles calculations that the effect of the coupled inhibition of hydrogen dissociation and entry on Fe(110) surfaces by CO and O_2 depends on the ratio of their coverage. Gaseous impurities mainly affect the process of hydrogen entering the material, but hardly affect hydrogen diffusion. Currently, the majority of research focuses on the impact of a single gas impurity on HE. However, in natural gas environments, a variety of gas impurities can potentially affect HE. Limited research has been conducted on the potential impact of multiple gas impurities on the HE of materials. Hence, further research on the impact of various gaseous impurities in natural gas on the HE of pipeline steels is essential. In addition, inhibiting HE in pipelines is a crucial concern that can be addressed by regulating gas components, potentially by introducing gas inhibitors or by setting limits on gas components that promote HE.

2.3.2 Effect of hydrogen on weld joints

Welding, which includes longitudinal, girth, and spiral techniques, is a critical component of pipeline infrastructure that requires careful consideration when assessing design and integrity. Welds can exhibit distinct strength, microstructure, macroscale defects, and residual stresses in comparison to the base metal (Sharma and Maheshwari 2017). Ronevich et al. (2021) showed that fracture resistance of pipeline welds in hydrogen decreases with increasing strength. Furthermore, welds and base metals of similar strength exhibit similar fracture behaviour in a hydrogen environment. However, Nguyen et al. (2020) found that a weld in X70 pipeline steel is more vulnerable than the base metal to hydrogen environment-assisted cracking. Research into pipeline steel welds is limited and controversial, with certain investigations indicating that welds exhibit greater susceptibility to HE than the base metal (An et al. 2019; Nguyen et al. 2020), while others report that welds do not demonstrate higher HE sensitivity (Ronevich et al. 2020; Ronevich et al. 2021).

The HE sensitivity of a weld is more complicated than that of the base material because of the following factors:

Higher HE sensitivity of microstructures: Compared with the base material, the microstructure of welded joints may be more sensitive to HE. Zhang et al. (2017) investigated the HE sensitivity of different sub-regions of X80 pipeline steel heat-affected zones (HAZ) through welding thermal simulation. The HE index for different sub-regions of HAZ from low to high is intercritical HAZ, fine-grained HAZ (FGHAZ), and coarse-grained HAZ (CGHAZ). Heterogeneous chemical structure and heat input during welding promotes different microstructures through the thickness, with associated disparities in hardness. For a given welding procedure, HAZ may have some ‘hard spots’ (Kappes and Perez 2023), such as some martensite microstructures, which are more sensitive to HE.

Higher local hydrogen concentration: Research indicates that the mechanical properties of steel deteriorate significantly only when its hydrogen concentration surpasses a critical threshold, making this critical hydrogen concentration a key parameter for assessing a material's resistance to HE (Fangnon et al. 2021). Qin et al. (2023) suggest that this threshold may correlate with the type and size of non-metallic inclusions. Wang's (2009) studies reveal that for X70 pipeline steel, fracture toughness only declines when hydrogen concentration exceeds 1ppm. Similarly, Capelle et al. (2011) examined the correlation between the initiation work of notch-induced local fractures and hydrogen concentration in X52, X70, and X100, uncovering critical hydrogen concentrations in the materials. Furthermore, as the hydrogen concentration increases, so does the risk of hydrogen-induced cracking. The distribution of hydrogen concentration is more complex in welds than in base materials.

Firstly, the microstructure of a weld can lead to varying hydrogen permeation behaviour. Zhao et al. (2018) measured the hydrogen diffusion coefficient of each sub-zone of X80 welding with a gaseous hydrogen permeation test, and the order from high to low was CGHAZ > weld material (WM) > FGHAZ > base material (BM). This result is different from that obtained by Xue and Cheng (2013) through the Devanathan-Stachurski cell test, where HAZ showed the smallest hydrogen diffusion rate and the highest hydrogen trapping density, while the X80 base material had the lowest hydrogen trapping density and the maximum hydrogen diffusion coefficient. Furthermore, due to the use of multi-layer and multi-pass welding techniques in the pipeline welding process, the HAZs of adjacent welding passes may affect one another, leading to the formation of intricate microstructures. Zhao et al. (2021) further investigated the hydrogen diffusion coefficient of the microstructure in the welded joint. The order of diffusion coefficients from high to low is acicular ferrite, granular bainite, lath bainite, polygonal ferrite, and M-A constituent.

Secondly, the stress gradient can induce hydrogen diffusion (Dwivedi and Vishwakarma 2018; Shang et al. 2020b; Martin and Sofronis 2022). During operation, the stress field of a weld joint is not uniform, mainly due to the following two points:

1.Welding residual stress is caused by incompatible plastic strain due to a heterogeneous temperature field in the welding process. Hydrogen will diffuse to accumulate in regions of larger tensile stress (Jiang et al. 2007; Jiang et al. 2022).

2.A sudden change in material mechanical performance and geometrical parameters in the structural components may increase the stress concentration. In a weld joint, the existence of welding defects (such as pores, inclusions, and cracks), unreasonable design of welded joints, and the different mechanical properties of microstructures all cause stress concentration. A few studies suggest that stress concentration could cause hydrogen diffusion and elevate the sensitivity of structural materials to HE (Shang et al. 2020b; Nguyen et al. 2021).

Optimising the hydrogen resistance of welds and developing anti-HE welding technology are challenging tasks. Our discussion highlights the idea that the key to anti-HE welding technology is exercising high sensitivity to HE while controlling the microstructure to prevent local hydrogen accumulation, which could result from uneven stress distribution and microstructure.

3 Design and operation

3.1 Pipeline design

Hydrogen-induced degradation of the mechanical properties of pipeline steel affects hydrogen-pipeline design. Currently, the primary criteria used to guide hydrogen-pipeline design include ASME B31.12-2019, CGA G5.6-R2003, AIGA 033-2014, and IGEM/TD/1 Edition 6 Supplement 2. An example of the most widely used guideline, ASME B31.12-2019 'Hydrogen piping and pipelines', provides Equation (1) to determine pipeline wall thickness.

$$P = \frac{2St}{D_o} F E_1 T H_f \tag{1}$$

where P is the design pressure, MPa; S is the specified minimum yield strength, MPa; t is the nominal pipe-wall thickness, mm; D_o is the nominal pipe outside diameter, mm; F is the design factor; E_1 is the longitudinal weld factor; T is the temperature discount factor; and H_f is the material property factor; all of which can be selected according to the table given by ASME.

A crucial safety parameter in ASME B31.12-2019 is the design factor F. ASME B31.12-2019 provides two options for calculating the design factor: Group A, with a maximum F of 0.5, is the prescriptive design factor requiring the material's strength and toughness to meet specific criteria. Group B, with a maximum F of 0.72, is the performance-based design method, which requires testing the mechanical properties in a hydrogen environment according to ASME BPVC VIII.3 KD 10. A crucial step is to ensure that the maximum stress intensity factor K_{IA} for a typical elliptical crack (depth = t/4 , length = 1.5t,) is less than the material's threshold stress intensity values K_{IH} in a hydrogen environment, and it should be ensured that $K_{IH} \geqslant 55$ MPa • $m^{1/2}$. Table 2 displays the arrest stress intensity factors K_{TH} in hydrogen environments for some materials tested using the constant displacement method. Group B design coefficients are based on the actual mechanical properties of the pipeline materials in hydrogen environments. Therefore, it is basically the same as the design factor in ASME B31.8, and the material performance coefficient can be 1.

Table 2 K_{TH} for crack arrest toughness in hydrogen environments

Material	Hydrogen pressure (MPa)	K_{TH} (MPa • $m^{1/2}$)	Ref
JIS-SCM435	35 115	53.2 44.3	(Matsumoto et al. 2017)
SCM435	45	55*	(Wada et al. 2005)
A106 Gr.C	97	55*	(Loginow and Phelps 1975)
X100	21 103 138	85 43–56 59	(Somerday et al. 2007; Nibur et al. 2009)

*** represents no crack propagation in hydrogen environments**

Compared with the natural gas pipeline design formula, Equation (1) additionally introduces a material performance factor of less than 1 to reflect the effect of hydrogen on the material. The value of this factor is based on the notched round bar tensile test in a high-pressure hydrogen environment, which was carried out by NASA (Walter and Chandler 1969) in 1969. Fig. 1 presents a linear regression analysis, depicting the relationship between the material performance coefficient and the square root of the hydrogen pressure. The values of the material performance coefficients adhere to two key assumptions. Firstly, the material performance factor exhibits a linear correlation with the square root of the hydrogen pressure following Sievert's law. Secondly, the material performance factor displays linearity proportional to the material flow stress, which represents the average of the specified maximum ultimate tensile strength and minimum yield strength.

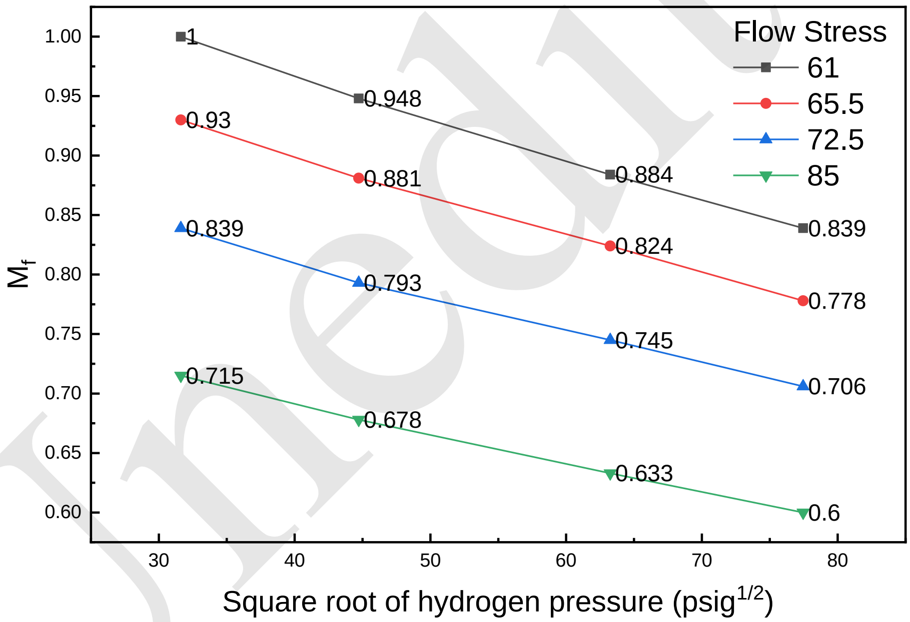

Fig. 1 Linear fit for the material performance factor in ASME B31.12-2019 Table IX-5B

The increasing understanding of HE and the accumulation of data on material properties in hydrogen environments indicate that the tensile and yield strengths of low- and medium-strength-grade pipeline steel are almost unaffected by hydrogen, but the fracture toughness is reduced (San Marchi and Somerday 2012). The material performance factor controls the allowable stress of the material in hydrogen environments due to the effect of hydrogen on the material. Conservative values are employed because they do not realistically reflect the effect of hydrogen on material properties. This condition results in a substantial increase in the wall thickness of the hydrogen pipeline, which entails additional material expenses and escalates welding costs (Brown et al. 2022). ASME B31 Code Case 218 deals with certain conditions under which material performance factors are removed. Residual stresses in welded joints are managed through post-weld heat treatment (PWHT) to guarantee that the critical flaw size calculated by the failure assessment diagram is greater than the lower limit of non-destructive testing. For materials with yield strengths exceeding 56 ksi, 100% hardness testing is required. Xu and Rana (2023) showed that compared with the introduction of material performance factor, PWHT can significantly improve damage tolerance in the pipeline and maintain comparable or better fracture resistance while reducing wall thickness.

3.2 Hydrogen velocity

Currently, the velocity design for long-distance hydrogen pipelines is usually based on natural gas pipelines, with a maximum velocity limit of 20 m/s. However, because hydrogen has a volumetric energy value that is only one-third that of natural gas, a higher gas velocity is needed to improve the efficiency of energy delivery under the premise of ensuring safe operation of the pipeline (Kuczyński et al. 2019). Table 1 compares certain parameters that affect the process of hydrogen and natural gas transmission (Herib Blanco et al. 2019; Topolski et al. 2022). The Panhandle equation states that, while maintaining pipeline operating parameters (such as upstream and downstream pressure), the flow rate of hydrogen is higher than that of natural gas due to the significant differences in their physical properties, such as hydrogen's lower density and viscosity. Therefore, the current upper limit of flow rate for natural gas pipelines may not be applicable to hydrogen pipelines. This could limit the efficiency of gas transmission in hydrogen pipelines.

$$q_{\mathrm{v}} = 1051\left[\frac{\left(P_1^2 - P_2^2\right)d^5}{\lambda Z \Delta T L}\right] \tag{2}$$

Where q_{v} is the volumetric flow rate ($\mathrm{m^3/d}$); P_1 is the upstream pressure (absolute) (MPa); P_2 is the downstream pressure (absolute) (MPa); d is the inner diameter of the gas pipeline (cm); λ is the hydraulic friction coefficient; Z is the gas compression factor; Δ is the specific gravity of gas in the pipeline, relative to air; T is the average temperature of gas in the pipeline; and L is the length of the calculation section of pipeline.

Economy and safety are the two main criteria that affect the selection of velocity in hydrogen pipelines. As mentioned in AIGA 033-1, 'There are no special velocity restrictions for piping in hydrogen service other than the underlying economics'. However, the publication notes that increasing gas velocity can cause issues such as erosion and vibration, which may affect the safety of the pipeline. Therefore, gas velocity should be selected based on the most economical option within the safe velocity range.

Table 1 Differences in physical properties between hydrogen and natural gas (Baird et al. 2021)

Property	Hydrogen	Comparison	Influence in process
Density	0.089 kg/m3 (0 ℃, 1 bar)	1/10 of natural gas	Compression; Flow resistance
Energy per unit of mass (LHV)	120.1 MJ/kg	3× of natural gas	Energy supply
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas	3× volumetric flow rate of hydrogen to supply the same energy at the same delivery pressure and pipe diameter
Sound velocity	1320 m/s (27 ℃)	3× of natural gas (450 m/s)	Ultrasonic flowmeter; Noise level
Viscosity	0.0088 cp (25 ℃)	0.69× of natural gas (SG = 0.5)	Lower flow resistance

Higher gas velocity in newly built hydrogen pipelines allows the utilisation of smaller pipeline diameters with the same gas-delivery capacity, reducing material and construction costs associated with pipeline development. In contrast, larger volumetric flow rates are necessary for natural gas after hydrogen blending to compensate for the resulting decrease in calorific value. If the current pipelines are not altered, the gas velocity within them needs to be increased. Doing so can significantly improve the efficiency and cost-effectiveness of a hydrogen-pipeline system. Higher gas velocity can achieve better transport efficiency, but the following limitations need to be considered:

Pressure drop: For natural-gas pipelines blended with hydrogen, although the pressure drop of the pipeline decreases due to the lower flow resistance of the H_2/NG with the same volumetric flow rate (Uilhoorn 2009), this state will result in a decrease in the energy transported by the pipeline. The increase in gas velocity will lead to an increase in pipeline pressure drop to ensure the same energy flow rate (Abd et al. 2021; Abbas et al. 2021). With the same pipeline pressure ratio guaranteed, blending hydrogen can increase the volumetric flow rate of the gas. However, doing so cannot compensate for the decrease in transported energy due to the lower calorific value of the mixed gas. The pipeline reaches the minimum transported energy when the hydrogen-blending ratio reaches 82% (Galyas et al. 2023). Balancing higher delivery efficiencies and increased pressure drops caused by higher gas velocity is a pressing concern. Although higher gas velocity is expected to improve transport efficiency, it can also result in higher gas-compression operating costs due to the increased pressure drops.

Erosion: As gas velocity rises, the turbulent intensity within the pipeline escalates, causing increased erosion of its components. Pipeline erosion, defined as the purely mechanical removal of matrix metal due to the impact of solid particles (Thiruvengadam 1974), is a significant challenge in natural gas pipeline design. Typically, the erosion velocity has an upper limit of around 20 m/s. Erosion velocity is calculated using the formula outlined in API RP 14E.

$$V_{\mathrm{e}} = \frac{c}{\sqrt{\rho_{\mathrm{m}}}} \tag{3}$$

where c is the empirical constant, $\sqrt{\mathrm{kg/(m \cdot s^2)}}$, and ρ_{m} is the gas/liquid mixture density at flowing pressure and temperature, $\mathrm{kg/m^3}$.

However, Madani Sani et al. (2019) assert that this formula lacks a strict theoretical basis, with insufficient consideration given to the factors that influence it. Therefore, increasing the upper limit of the erosion velocity might be advisable considering recent practical evidence. Such evidence shows that natural gas pipelines can operate dependably at an elevated erosion velocity that exceeds the conservative estimates based on the formula outlined in API RP 14E.

Furthermore, erosion is linked to the mechanical characteristics of materials. Nonetheless, as a result of HE, materials' mechanical properties can degrade significantly, potentially resulting in a synergistic interaction between erosion and HE.

Noise and vibration: High-velocity gas flowing through a pressure reducing device can result in acoustic-induced vibration. High-frequency sound waves can excite the circumferential mode of vibration of pipes and may result in fatigue failure at welded attachments where stress concentration occurs (Prakash et al. 2015).

The noise level increases at higher flow rates. ASME B31.12 enforces a maximum noise level of 110 dBA for hydrogen pipelines. Furthermore, because of the elevated sonic velocity, potential problems may arise at pressure differentials that would not have been problematic with the majority of other gases.

In summary, to enhance the efficiency of energy delivery, hydrogen requires a higher velocity. The pivotal question pertains to establishing this upper limit, necessitating a comprehensive consideration of the aforementioned influencing factors. However, current studies tend to concentrate on the influence of velocity on a single indicator without comprehensively evaluating other factors (Koo et al. 2023; Juez-Larré et al. 2023). Therefore, a method that can effectively guide the determination of hydrogen velocity needs to be developed. Furthermore, the existing research predominantly centres around theoretical calculations, but their validity and applicability to hydrogen have not been extensively assessed. Conducting further experimental investigations aimed at refining and establishing theoretical models that can be employed effectively and reliably in the context of hydrogen gas is thus of the utmost importance.

3.3 Security management and monitoring

3.3.1 Integrity management

Flaws are inevitably present in pipelines during operation, and these flaws can potentially expand and lead to pipeline failure as gas pressure fluctuates. The presence of hydrogen can accelerate this process, making pipelines more vulnerable to failure (Chong et al. 2013). A failure assessment can be conducted to estimate the remaining lifespan and strength of the pipeline, and flexible adjustments of operational parameters during operation can ensure that the integrity of the pipeline is maintained.

Failure assessment diagrams (FADs) are widely used in the evaluation of pipeline failures with flaws and have come to form a relatively complete standard system (e.g. API 579, BS 7910, GB/T 19624). FADs consider both brittle fracture and plastic collapse and can determine three failure modes: brittle fracture, fracture + plastic deformation, and plastic collapse. In practical use, the L_r (load ratio = the ratio of the reference stress for primary loads to the yield strength) and K_r (toughness ratio = the ratio of the stress intensity factor K_I to the fracture toughness K_{IC}) are calculated based on the specific working conditions, material properties, and size of flows. When the assessment point (L_r, K_r) falls inside the curve, the pipeline is considered safe. The points on the failure curve correspond to the critical defect size of the structure under the load.

As shown in Fig. 2, hydrogen can significantly decrease the fracture toughness of materials, leading to increased Kr, an upward shift in the coordinates of the assessment point, and an increase in the proportion of flaws that were originally deemed acceptable but are now deemed unacceptable. This condition could reduce the critical crack size, ultimately impacting the remaining pipeline strength (Ishikawa et al. 2022). If there are large-scale cracks in the pipeline, it may be necessary to reduce the operating pressure to ensure its integrity.

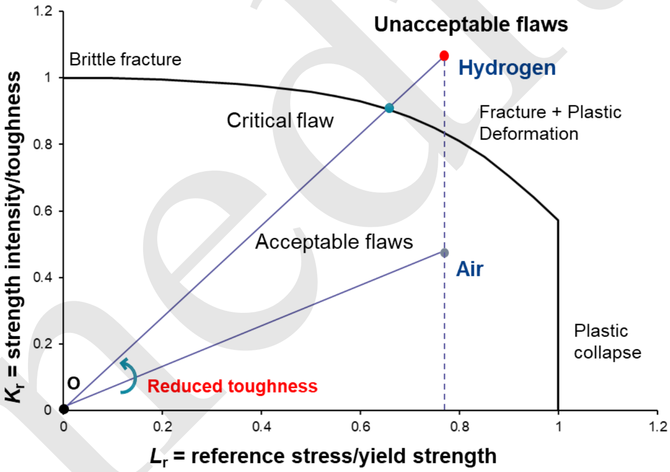

Fig. 2 Failure assessment diagrams and the effect of hydrogen

The fatigue crack growth curve is used to determine the remaining life of a pipeline. For low-carbon alloy pipeline steel, the FCGR at a lower ΔK is typically not impacted by hydrogen. However, at a higher ΔK, the FCGR in hydrogen environments is usually one to two orders of magnitude higher than in air environments. Furthermore, the difference in the FCGR between pipeline steels with different material strengths is relatively small in hydrogen environments.

Therefore, in the absence of test data, ASME B31.12 proposes a relatively conservative envelope-design fatigue crack growth curve based on the existing FCGR data (Slifka et al. 2018; Dadfarnia et al. 2019)

$$\frac{\mathrm{d}a}{\mathrm{d}N} = a_1 \Delta K^{b_1} + \left[(a_2 \Delta K^{b_2})^{-1} + (a_3 \Delta K^{b_3})^{-1} \right]^{-1} \tag{4}$$

Table PL-3.7.1-5 in ASME B31.12 provides all the constants for Equation (4). This formula is suitable for hydrogen gas pressures of less than 20 MPa and stress ratios of less than 0.5. Sandia (San Marchi et al. 2019; San Marchi and Ronevich 2022) delved deeper into the impacts of gas pressure and stress ratio on the FCGR, classifying the curve based on the magnitude of ΔK. At a lower ΔK, the FCGR shows a correlation with gas pressure and stress ratio, but at a higher ΔK, it is independent of pressure.

At a high ΔK,

$$\frac{da}{dN}=1.5\times10^{-11}\frac{1+0.2R}{1-R}\Delta K^{3.66} \tag{5}$$

and at lower ΔK,

$$\frac{da}{dN}=3.5\times10^{-14}\frac{1+0.4286R}{1-R}\Delta K^{6.5}P^{0.5} \tag{6}$$

where R is the pressure ratio and P is the hydrogen pressure.

3.3.2 In-line inspection

As mentioned above, hydrogen can decrease the fracture resistance of metal materials, resulting in pipelines that contain flaws being more susceptible to failure. Therefore, in-line inspection for hydrogen pipelines requires a high accuracy grade (Kim Domptail et al. 2020).

Currently, the inspection technology for natural gas pipelines has matured, relatively speaking. The prevalent use of magnetic flux leakage testing (Chen et al. 2023) and the emerging application of ultrasonic testing hold promise for hydrogen pipelines. Both techniques require the use of permanent magnets. However, early research has indicated that NdFeB permanent magnets tend to absorb significant amounts of hydrogen under normal conditions, leading to a decline in their magnetic properties and consequently to a reduction in the quality of the inspection signal. Furthermore, the magnet volume can expand by as much as 2.8% to 4% because of the significant uptake of hydrogen, leading to material fragmentation if the internal stress exceeds the material's fracture strength. An investigation by T.D. Williamson (Morris and Barker 2021) highlighted that just 10% of hydrogen in methane can adversely affect functioning of the inspection equipment, while as little as 500 ppm of hydrogen is enough to cause permanent damage to the permanent magnet. Rosen also notes that detectors used in hydrogen environments require protective measures to preserve their magnetic circuits.

3.4 Knowledge gaps for building a low-cost and high-reliability hydrogen pipeline

The cost of constructing hydrogen pipelines is greater than that for natural gas pipelines. As discussed above, material experiments have demonstrated that hydrogen can significantly degrade the mechanical properties of pipeline steels. Consequently, the industry customarily employs a substantial safety factor to regulate the circumferential stress of hydrogen pipelines, maintaining it at a relatively low level to mitigate the risk of pipeline failure in hydrogen environments. This approach necessitates the implementation of more substantial design thicknesses for hydrogen pipelines (Fischer et al. 2023). Knowledge gaps remain in terms of ensuring pipeline safety while fully utilising the mechanical properties of materials, including the following points:

1. As mentioned previously, ASME B31 Committee approved Code Case 218 for relaxation of material performance factors. However, specific conditions must be satisfied before the material performance factor can be set to 1 for pipelines: 'para. PL-3.7.1(1) Option A (Prescriptive Design Method) shall be used and the material performance factor H_f shall be 1.0'. In addition, no equivalent exemption permit for industrial piping in Part IP, similar to Option B for pipeline in Part PL, would enable the material performance factors to be set to 1. This observation implies that the code case is primarily applicable to industrial piping rather than to pipelines. Further research is needed to find a more reasonable pipeline design method that could replace the existing material performance factors.

2. When pipelines are exposed to external loads in addition to internal pressure, such as in regions characterised by frequent geological activity, the resulting strain typically exceeds the yield strain associated with the yield strength (typically 0.5%). Nevertheless, the pipeline maintains a certain level of structural capacity. The stress–strain curve shows that when the stress exceeds the yield strength, the use of strain control is more accurate, leading to the development of strain-based design (SBD) (Liu et al. 2009; Agbo et al. 2019; Guy et al. 2021). SBD allows a more effective use of the pipeline's longitudinal strain capacity while maintaining the hoop pressure containment capacity (Macia et al. 2010). SBD has

been widely implemented in natural-gas pipelines. Pertinent standards include DNV-OS-F101, CSA-Z662, and ASME B31.8. SBD necessitates that pipeline steels have a significant deformation capability to avoid failure (Park and Gianetto 2019). However, the presence of hydrogen can substantially decrease the tensile strain capability of pipeline steels and their welds, especially when defects are present (Andrews et al. 2018). Therefore, further research is necessary to determine the permissible deformation capacity when utilising SBD in the design of hydrogen pipelines or assessing hydrogen blending in natural gas pipelines built using SBD.

3. Stress-based design is typically employed for designing hydrogen pipelines, assuming zero defects. Wall thickness is determined based on material strength, while a higher safety factor is used to guarantee safety in hydrogen environments, leading to suboptimal material utilization. Building high-quality hydrogen pipelines requires considering the performance of materials in a hydrogen environment. However, some findings suggest that predicting the impact of hydrogen on pipelines based on laboratory testing is overly conservative and inaccurate (Andrews et al. 2022). At present, the majority of techniques employed to assess pipeline failures (including pitting, volumetric corrosion, and mechanical interference) are semi-empirical and have been certified using full-scale pipelines that do not come into contact with hydrogen. Therefore, some argue that current research may exaggerate the harm caused to pipelines by hydrogen, especially when considering plastic collapse as the failure mode (Andrews et al. 2022). Additionally, the fracture toughness of materials has a close relationship with crack tip constraint, but the constraint at the crack tip in commonly used compact tensile specimens differs significantly from that of pipelines (Dadfarnia et al. 2011; Li et al. 2018). There is a critical need to carry out full-scale pipeline experiments in order to more comprehensively determine the impact of hydrogen on pipelines. Nonetheless, there is a significant dearth of experimental information in this domain (Hoover et al. 1981; Holbrook et al. 1982; Holbrook et al. 1984; Capelle et al. 2008; Elazzizi et al. 2015).

4 Repurposing of natural gas assets

4.1 Hydrogen-blending adaptability evaluation

Building new hydrogen pipelines involves substantial investment costs and a prolonged duration. However, repurposing existing natural gas pipelines for hydrogen transportation can result in rapid hydrogen transport while significantly reducing capital costs (75% to 90% [Tsiklios et al. 2022]). Moreover, converting existing natural gas pipelines into hydrogen pipelines can prevent their abandonment in subsequent decarbonization processes. Several countries are currently engaged in research related to blending hydrogen in natural gas pipelines, including HyDeploy in the UK, NATURALHY in the EU, and HyBlend in the US. The results show that a low concentration of hydrogen has little effect on the integrity or operation of pipeline systems, including transmission pipelines, distribution pipelines, and terminal equipment (Melaina et al. 2013). Given the current situation, ongoing and proposed projects are aiming for even higher hydrogen concentrations, with some even targeting the transportation of pure hydrogen.

Fig. 3 depicts the process of blending hydrogen in natural gas pipelines and highlights potential challenges. The system includes natural gas extraction, hydrogen production, gas mixing and separation, transmission pipelines, stations, distribution pipelines, and end users.

The conversion of existing natural gas pipelines into hydrogen pipelines requires an adaptability evaluation based on the collected pipeline data. One of the crucial parameters in this evaluation is the hydrogen-blending ratio. As the blending ratio increases, the hydrogen partial pressure intensifies, leading to a more severe HE for the pipeline steels (San Marchi and Somerday 2012). In addition, the transported energy decreases (Galyas et al. 2023), which can be compensated for by increasing the gas flow velocity. However, these two changes present a contradiction. The former necessitates a reduction in operating pressure to ensure safe operation of the pipeline, while the latter requires higher pressure to counteract the increased pressure drop resulting from the elevated flow velocity.

Furthermore, the inclusion of hydrogen can affect the normal functioning of certain equipment, such as ultrasonic flow metres (Ullmann 2022), compressors, and certain electronic components

(Baba et al. 1990; Lee et al. 2010).

The hydrogen-blending ratio is also subject to regulatory constraints imposed by natural gas regulatory limits. Currently, the upper limits of hydrogen-blending ratios in various countries' regulations are significantly different (Erdener et al. 2023). For instance, Germany has set an upper limit as high as 10%, while Japan, the UK, and California (US) have restricted the hydrogen-blending ratio to below 0.1%. However, it is reasonable to believe that the value will steadily increase as research on the blending of hydrogen with natural gas progresses.

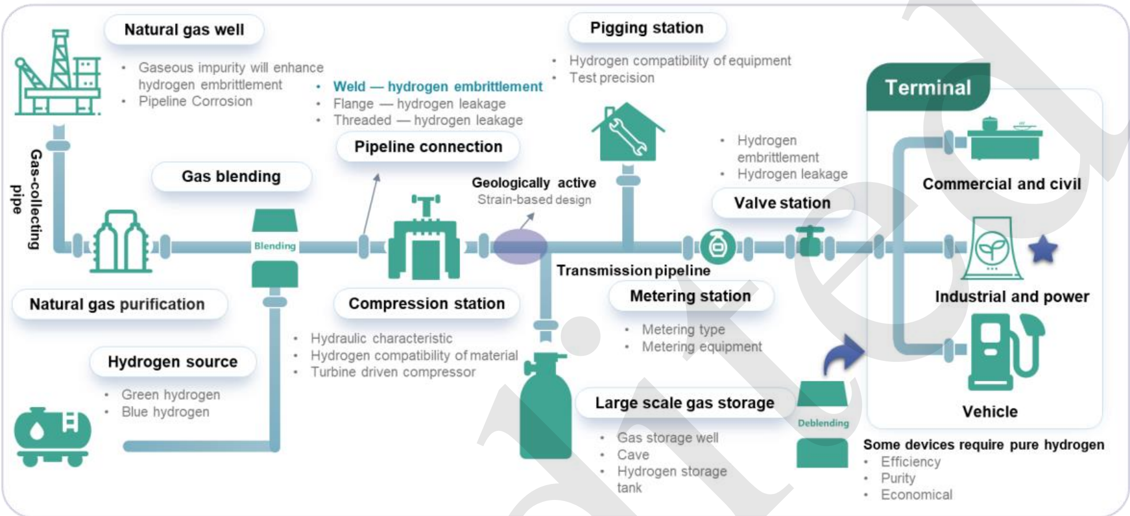

Fig. 3 Process and problems of hydrogen blending into natural gas. Gas sources: extraction and purification of natural gas, sources and mixing of hydrogen gas; Transmission pipelines: gas compression, pigging, metering, storage and valve chambers; Distribution pipelines: gas separation and delivery to end users

Currently, considerable research (Melaina et al. 2013; Topolski et al. 2022) has evaluated the impact of hydrogen blending on natural gas pipelines. As illustrated in Fig. 4, this paper categorises these effects into five aspects: hydrogen compatibility of material, device functional reliability, process suitability, leakage explosion hazard, and adaptability of end-use hydrogen equipment. The comprehensive evaluation of hydrogen's influence on existing natural gas pipeline materials, processes, equipment, and safety management is imperative for the development of a universally applicable methodology for hydrogen-blending assessment. The subsequent discussion highlights persisting challenges in the repurposing of existing natural gas pipelines.

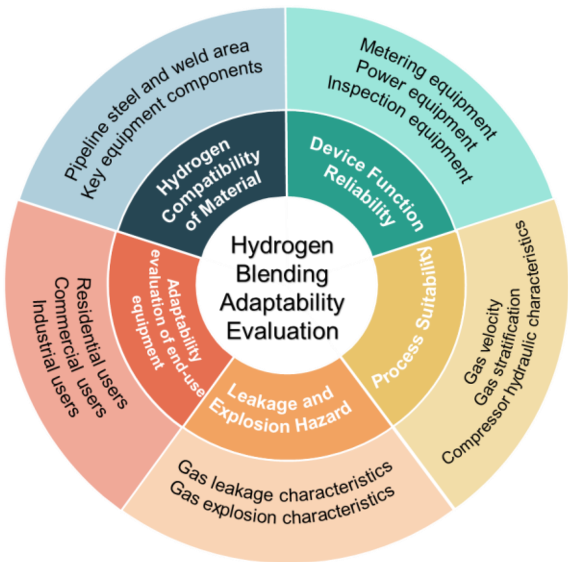

Fig. 4 Hydrogen-blending adaptability evaluation

4.2 Knowledge gaps in hydrogen-blending adaptability evaluation

1.Although many projects and studies have been conducted on hydrogen blending for natural gas pipelines, the current research approach remains predominantly case by case. Most projects only present findings on the suitability of a specific pipeline for hydrogen blending and the maximum allowable hydrogen-blend percentage. A comprehensive methodology that can be universally applied to guide the evaluation of natural gas pipeline adaptability to hydrogen blending is lacking. With regard to the repurposing of existing natural gas pipelines for hydrogen delivery, some of the major existing codes are summarised in Table 2. However, researchers have realized that there are still many improvements that need to be made. Over-prescriptive sampling and testing approaches that are not risk-based are presented in ASME B31.12-2019, CAG G5.6-R2013, and AISA 033-2014; these will be described in more detail below. IGEM/TD/3 Edition 5 Supplement 1 is not suitable for high-pressure pipelines. Appendix H of ISO 13623, ‘Petroleum and natural gas industries - Pipeline transportation systems’, is under development. It will provide a pre-defined process for converting existing pipelines for hydrogen service, but it is closer to a general requirement rather than a specific technical regulation.

2.Most natural gas transmission pipelines are heavily regulated, with volume limits for hydrogen typically well below 10% and often controlled to less than 0.5% (Erdener et al. 2023). Authorisation from the operators is required for additional blending of hydrogen. However, most current natural gas pipeline operators refuse to blend hydrogen because of a lack of operational experience (García Martín 2022; Bautista and Hall). Therefore, operators should be encouraged through external studies and pilot tests to adopt the new blending standard. Another important consideration is to harmonise the new standard with other existing regulations. For instance, the current standard for gas turbine control systems and seals in Europe requires a hydrogen content of less than 1% (García Martín 2022).

3.The current evaluation of the adaptability of natural gas pipelines to hydrogen blending covers multiple aspects such as materials, processes, design, operation and maintenance, and economics (Erdener et al. 2023). These factors have correlations. For instance, upon rapid valve closure, gas mass flow abruptly falls to zero, leading to the water hammer phenomenon and an increase in upstream pressure. Compared to natural gas, hydrogen can reach higher pressures. This has a synergistic effect with HE, making the pipeline more prone to failure (Bouledroua et al. 2020). Further exploration is needed to comprehensively consider the correlations between the various factors and develop a set of evaluation methods for assessing the adaptability of natural gas pipelines to hydrogen blending.

4.As metallurgical technology continues to develop, even within the same grade of pipeline steel, vintage and modern materials will have different chemical composition and mechanical properties. Typically, modern materials have a lower carbon equivalent and improved weldability. In addition, research by NIST has shown that modern X52 has a smaller grain size than that of vintage X52 (Slifka et al. 2018). Notably, the Charpy V-notch impact toughness requirement for API 5L PSL2 steel pipes was not included in the standard until after 2000. Therefore, the performance of vintage pipeline steels in hydrogen environments needs to be tested. However, several challenges exist within this context (Sandana et al. 2022). Firstly, the design, construction, and maintenance records of these pipelines may be incomplete, making it more difficult to understand their current condition. ASME B31.12 specified physical and chemical analysis to be conducted at intervals of 1.6 km for pipelines that lack information, and the evaluation methods for welds and HAZs are even more stringent. Consequently, this situation significantly increases the complexity and cost of the assessment task. The cost and workload associated with such evaluations are often considered unacceptable in engineering. Secondly, as previously mentioned, the material performance and welding techniques in vintage pipelines may differ from those in modern pipelines. Moreover, long-term operation of natural gas pipelines causes the degradation of physical and mechanical properties of pipeline steels. Nykyforchyn et al. (2011) divided the degradation of pipeline steel properties over time into two stages:

deformation ageing and diffused damage development. The strength and hardness of the steel increase during deformation ageing. This condition is accompanied by a decrease in plasticity and resistance to brittle fracture. As damage within the material continues to accumulate, the strength and hardness of the steel eventually begin to decrease. Non-destructive techniques such as indentation and electrochemical methods are pivotal in assessing pipeline steel degradation under operational conditions. Indentation testing gauges hardness variations during operation, indirectly reflecting material susceptibility to HE (Bolzon and Zvirko 2017; Kappes and Perez 2023). Furthermore, electrochemical assessments highlighted by Zvirko et al. (2019) predict changes in impact toughness via polarization resistance measurements, elucidating the impact of operational degradation on pipeline steel.

Table 2 Current codes regarding repurposing of existing natural gas pipelines

Code	Title	Section
ASME B31.12 - 2019	Hydrogen piping and pipelines	Part PL 3.21 - steel pipeline service conversions
IGEM/TD/3 Edition 5 Supplement 1	Repurposing of natural gas pipelines with MOP not exceeding 7 bar for NG/hydrogen blends	/
CGA G5.6-R2013	Hydrogen Pipeline Systems	Appendix H - Requalification of existing pipelines for hydrogen service
AIGA 033-2014	Hydrogen Pipeline Systems	Generally consistent with CGA G5.6
ISO 13623:2017/DAM1	Complementary requirements for the transportation of fluids containing carbon dioxide or hydrogen	Appendix H.9 Repurposing

5 Conclusions

In recent years, the number of research projects and approved proposals related to hydrogen pipelines has increased significantly. However, several prominent challenges remain when it comes to ensuring safe and efficient transportation of hydrogen or hydrogen-blended natural gas through pipelines.

This study provides a comprehensive review of the current state of knowledge and gaps with regard to gaseous hydrogen pipelines, including hydrogen compatibility of material, design method, transportation processes, operation and maintenance, and the repurposing of existing natural gas assets. On the basis of this analysis, we propose the following recommendations:

Material: High-strength steel has immense potential for utilisation in hydrogen pipelines and could offer noteworthy advantages. Nevertheless, the use of high-strength steel in hydrogen atmospheres is presently hindered by crucial factors such as mechanical degeneration of welded joints. In addition, further research is needed on the impact of gas impurity in hydrogen-blended natural gas on the HE of materials.

Design: The current approach mandated in ASME B31.12 is relatively conservative, as the employment of material performance factors does not precisely indicate material performance loss in hydrogen environments. Though ASME B31 has approved Code Case 218 to eliminate material performance factors under specific circumstances, a performance-based design method for hydrogen pipelines is still needed. Testing the mechanical properties of materials in an in-situ hydrogen environment is necessary. However, the current data in this area is still insufficient.

Velocity: Gas velocity plays a crucial role in ensuring the economic viability and safety of pipeline operations. The considerable deviations in physical properties between hydrogen and natural gas highlight the need for further research to accurately estimate the optimal velocity of hydrogen or hydrogen-blended natural gas.

Integrity: Hydrogen-induced degradation of metallic materials aggravates the risk of pipeline failure. Consequently, higher precision and more frequent inspection cycles might be necessary for in-line inspection. Moreover, accounting for the fact that hydrogen has an impact on the magnetic components in the in-line inspection equipment is essential.

Repurposing: The research is still conducted on a case-by-case basis. A method and standard for evaluating hydrogen-blending suitability should be developed. The crucial aspect is acquiring a comprehensive understanding of the existing natural gas pipelines and identifying potential risk factors that could arise from hydrogen blending. In addition, determining the maximum hydrogen-blending ratio that the pipeline can withstand is of utmost importance.

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Author contributions

Zhengli Hua: Writing–review & editing, Writing–original draft, Investigation, Funding acquisition, Conceptualization. Ruizhe Gao: Writing–original draft, Investigation, Data curation. Baihui Xing: Writing–original draft. Juan Shang: Writing–review & editing. Jinyang Zheng: Writing–review & editing, Conceptualization. Wenzhu Peng: Writing–review & editing, Investigation. Yiming Zhao: Investigation.

Conflict of interest

Zhengli Hua, Ruizhe Gao, Baihui Xing, Juan Shang, Jinyang Zheng, Wenzhu Peng, Yiming Zhao declare that they have no conflict of interest.

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中文概要

题　目：氢气管道发展现状及挑战，从材料、设计以及完整性角度

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概　要：本文了回顾氢气管道及天然气管道掺氢的发展现状。涵盖了材料的氢相容性、氢气管道的设计方法、气体输送工艺、管道完整性评价与在线检测技术，以及天然气管道掺氢的评价方法。在此基础上，进一步指出了氢气管道建设过程中面临的一些挑战：1. 氢气管道中高强钢的应用；2. 高质量的氢气管道设计方法；3. 管道中氢气流速的选择；4. 现有天然气管道掺评价方法。最后，提出了对未来发展方向的一些建议。

关键词：氢气管道；氢脆；标准；管道设计；氢气流速