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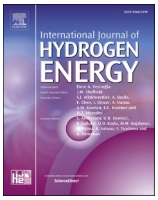

Advances in hydrogen blending and injection in natural gas networks: A review

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ABSTRACT

With growing concerns about carbon emissions and the need for decarbonization, hydrogen is a promising hypothesis for the replacement of fossil fuels. Blending hydrogen with natural gas and using existing natural gas transmission networks is a strategy that could reduce carbon emissions. However, a significant challenge with using hydrogen in transmission networks is its potential to cause embrittlement, compromising the structural integrity of pipelines. This paper provides an overview of the complexities involved in blending and injecting hydrogen into natural gas transmission pipelines and discusses methods to enhance system performance and mitigate these challenges by reviewing studies focused on these topics. The paper highlights the multidisciplinary nature of hydrogen injection into natural gas pipelines and discusses ongoing research efforts to address this issue. The study shows significant progress in the technological development of injection strategies, mixing solutions, sensors, and materials. Still, challenges remain regarding experimental work, sensors capable of operating in high-pressure transmission pipelines, and material solutions such as coatings that can inhibit embrittlement and be applied *in-situ* in operating pipelines. Although numerous numerical studies exist, experimental research on mixing and injection systems remains limited. While real-time measurement technology is advancing, more innovation is needed for high-pressure environments. New coatings and linings have been developed to mitigate embrittlement, but their application in operating pipelines requires further investigation.

1. Introduction

Global carbon dioxide (CO_2) emissions have reached unprecedented levels, primarily driven by intensified reliance on coal and compounded by adverse weather conditions, escalating natural gas prices, and slow growth in renewable energy [1]. In May 2021, the International Energy Agency (IEA) published its landmark report [2], outlining a narrow yet achievable pathway for the global energy sector to align with the 2015 Paris Agreement's objective of limiting the temperature rise to 1.5 °C above the pre-industrial levels. Meanwhile, the ongoing surge in fossil energy consumption and CO_2 emissions underscores the critical imperative of achieving carbon neutrality to mitigate global warming, emphasizing the necessity to transition from conventional fossil fuels to carbon-neutral alternatives [3,4].

Hydrogen, the most abundant element in the universe, offers significant promise as an alternative energy source due to its higher heat release per unit mass and its capability for storage in large quantities. These characteristics make it an attractive alternative to conventional energy sources [5–7]. Furthermore, hydrogen is crucial for various applications like chemicals, fuels, and power [6,8]. Hydrogen and hydrogen-based fuels offer potential in decarbonizing challenging sectors like heavy industry and long-distance transport where emissions are difficult to decrease. Unlike fossil fuels, hydrogen combustion primarily generates water, thus mitigating CO_2 and other harmful emissions [9,10].

Hydrogen is rarely found in its natural state and must be obtained from other materials, thus requiring energy [11]. It can be produced from non-renewable sources (grey and blue hydrogen) or renewable sources (green hydrogen). Grey hydrogen, derived from methane through steam methane reformation, emits CO_2 into the atmosphere. In contrast, blue hydrogen also derives from methane. However, it includes carbon capture and storage to reduce CO_2 emissions, making it more

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suitable than grey hydrogen, although it is not entirely emission-free [11]. Green hydrogen is produced by electrolytic water or renewable sources, such as wind, biomass, solar, and geothermal. Hence, it contains zero carbon. After production, hydrogen is transported through transmission and distribution pipeline networks to generate energy for industries, residents, and transports [12].

Projections indicate that hydrogen will contribute over 19 % of final energy demand by 2050. However, transporting pure hydrogen faces cost and technical barriers [13]. One reasonable strategy, as depicted in Fig. 1, is blending it with natural gas (H2NG) and using the already-built natural gas pipelines for its transportation [14]. This strategy reduces overall carbon emissions and is economically feasible due to the established infrastructure and social acceptance of natural gas networks, making conversion more cost-effective than building dedicated hydrogen pipelines [15]. This transition can be gradual, in line with increasing hydrogen supply and demand, and benefits from the extensive geographical reach of natural gas networks. Furthermore, the technologies required for such conversions are already available and tested, making the repurposing of natural gas infrastructure for hydrogen transport a practical and economically advantageous solution [16]. The integration of hydrogen into natural gas networks requires a robust policy framework to address technical, regulatory, and market challenges. Key priorities include establishing standardized blending ratios to ensure safety and compatibility across different infrastructures and applications, while accounting for regional differences in pipeline materials and hydrogen production capabilities.

Policies should also emphasize rigorous, case-by-case technical and economic assessments to define allowable conditions for renewable hydrogen production and blending, paving the way for a sustainable and efficient transition [17]. Economic barriers hinder the integration of hydrogen into natural gas networks, with the high cost of green hydrogen and retrofitting pipelines posing challenges. Low blending ratios dilute benefits while higher ratios demand costly upgrades. Policymakers must balance costs, technical feasibility, and emission goals by introducing subsidies, tax incentives, and support for retrofitting and hydrogen hubs to stimulate investment. Carbon pricing mechanisms, like taxes or emissions trading, can further enhance hydrogen's competitiveness by accounting for the environmental costs of fossil fuels. However, due to the physical properties of hydrogen, there is a need to adapt the current systems by optimizing the blending ratios and introducing advanced materials and technologies [9].

The higher energy density of hydrogen compared to natural gas (145 MJ kg and 53 MJ kg) is offset by its nine times lower density, which affects the energy per unit volume, calorific value, and Wobbe index [18,19]. Higher flow rates and operating pressures are required to maintain the energy balance, resulting in increased pressure drops, especially at higher hydrogen concentrations [20–22]. Such pressure drops can strain the compressor and pipeline design limits set initially for natural gas transport [23,24], although some studies suggest that the impact may not be significant [19,25,26].

Despite these considerations, a far more pressing concern is that hydrogen atoms can penetrate the surface of pipeline steels, causing hydrogen embrittlement (HE) and hydrogen cracking [27–30], which decreases the tensile strength, fracture toughness, and fatigue strength of the pipeline [31–35]. Therefore, since hydrogen has a much lower density than natural gas, it will stratify, increasing pipe embrittlement and raising the risk of rupture. This non-uniform mixture throughout the pipeline exacerbates embrittlement in all transportation equipment [36–40]. To mitigate the risk of hazardous events in pipelines, achieving uniform transportation or developing new materials/coating is essential [41].

The number of ongoing worldwide hydrogen projects is significantly increasing [42]. Notable examples include the Hydeploy and H21 Leeds CityGate projects in the UK [43], DVG projects in Germany [44], Liaoning Chaoyang demonstration project in China [45], Hydrogen Park South Australia (HyP SA) in Australia [46], GRHYD in France [47], NaturalHy and THyGA project in the EU [48,49], and HyBlend and SoCalGas in the US [50,51]. These projects mainly focus on feasibility, safety, and infrastructure compatibility initiatives but also delve into specific blending methodologies and gas flow dynamics. Furthermore, the H2NG project in Portugal aims to develop a practical blending solution specifically for high pressure transmission pipelines [52]. In the

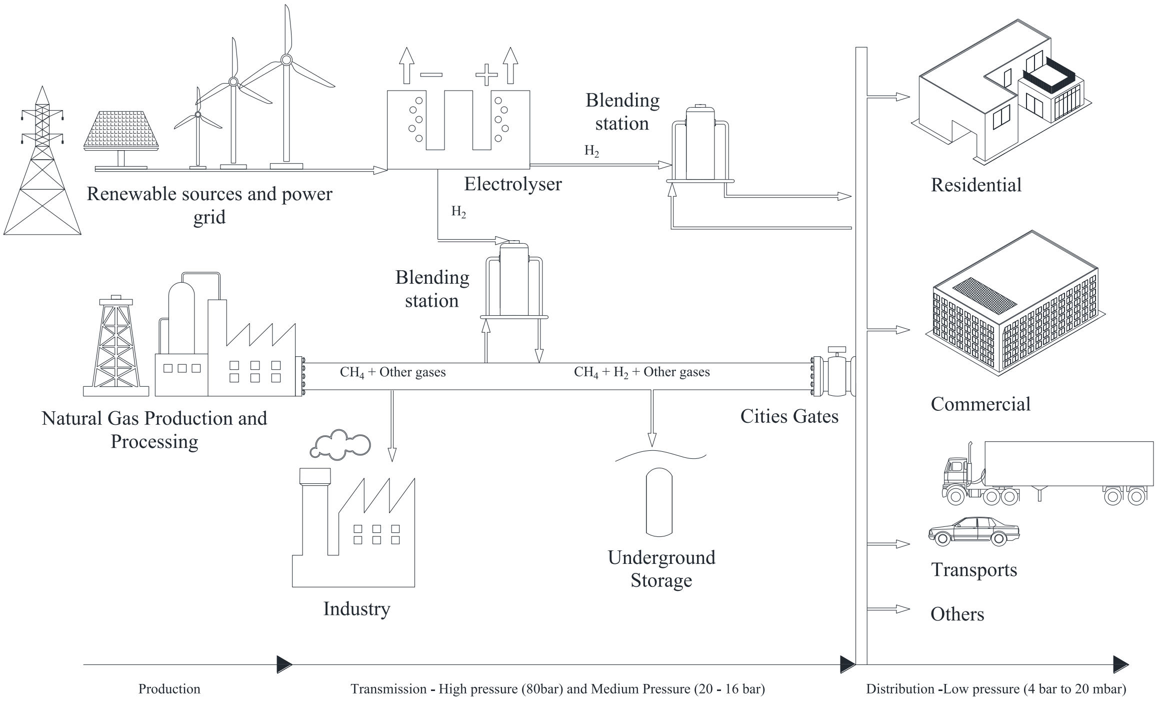

Fig. 1. Hydrogen production, gas network interaction and final distribution. Pressure values are characteristic values in transmission/distribution pipelines in Portugal [61].

literature, there is a debate about blending hydrogen with natural gas. While many publications highlight its potential to significantly reduce emissions, some authors caution against its long-term viability, citing concerns such as excessive investment required for pipeline repurposing [53]. Kappes and Perez [54] highlight the adverse impacts on materials and the risks, challenges in evaluating failure pressure, and the absence of international codes for hydrogen contents below 10 %. Another study emphasizes the importance of updating standards to include ductility parameters and fatigue testing for advancing hydrogen compatibility assessment in pipeline steel. It also suggests that standardizing testing protocols can improve evaluation and mitigation strategies for hydrogen embrittlement [55].

Lo Basso et al. [56] comprehensively explore the application of blends, covering technical, energy, environmental, economic, and safety aspects. Meanwhile, Jia et al. [45] discussed the global variation in natural gas composition and its fracture impact, focusing on blending ratios and improving material resistance to HE. The blending ratio emerges as a pivotal factor, balancing environmental benefits with economic and operation practicality [9]. While it is commonly believed that hydrogen mixtures up to 20 % volume have minimal impact, the threshold for operational effects can vary depending on network characteristics and end-users [57].

Other studies have focused on various aspects of hydrogen infrastructure development, including optimizing gas leakage detection equipment [58] and the necessity for efficient inspection and maintenance strategies [59]. Considering the costliness of hydrogen production and usage compared to alternative technologies, leveraging existing gas infrastructure is crucial, especially given the higher capital costs associated with electrolyzes, to ensure efficient hydrogen distribution [60]. However, a significant challenge with using hydrogen is its potential to cause embrittlement, which affects the integrity of pipelines and has not been adequately addressed in the literature. Comprehensive research covering the main strategies to mitigate hydrogen embrittlement is currently lacking in this area. Therefore, this study thoroughly reviews scientific publications on mitigation strategies to prevent hydrogen stratification within pipelines, available measurement systems for

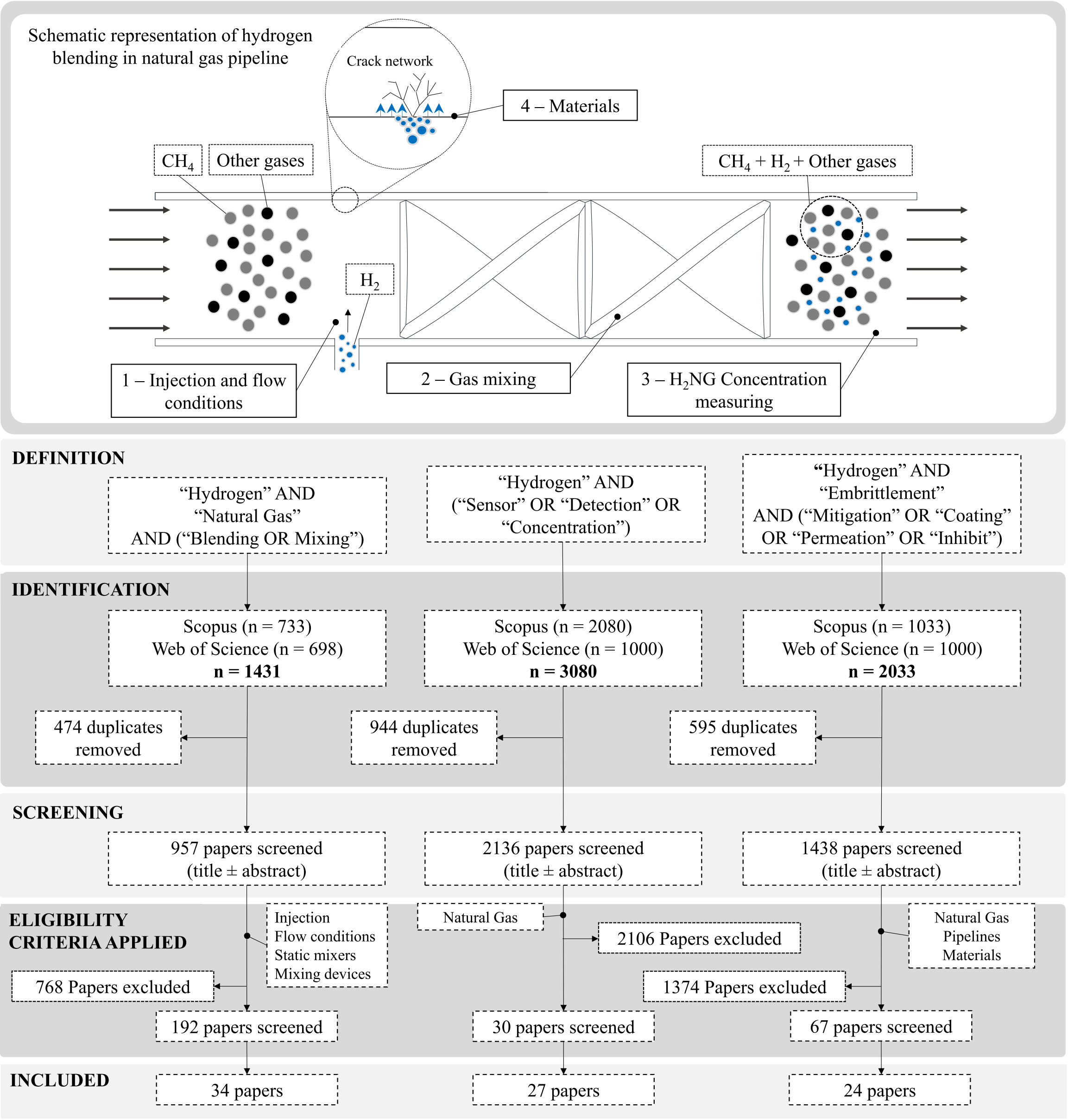

Fig. 2. Schematic representation of literature review using PRISMA.

controlling it, and other solutions such as gases, coatings/materials that may prevent hydrogen embrittlement.

While existing literature predominantly assesses hydrogen's impact on end-uses, our study uniquely emphasizes the critical importance of evaluating the transmission network. We focus on the infrastructure, consisting of high-pressure, wide-diameter pipelines that connect natural gas entry points to main consumer areas over long distances. This evaluation is crucial because the transmission network's susceptibility to hydrogen-induced damage presents significant challenges that have been largely overlooked.

More thoroughly, our review paper addresses the challenges of achieving uniform hydrogen-natural gas mixing in pipelines, exploring methods to reduce variation for consistent gas quality. We emphasize the importance of real-time gas concentration monitoring using advanced high-pressure sensor technologies as alternatives to traditional chromatography. Additionally, we assess pipeline materials for susceptibility to hydrogen embrittlement and discuss recent advancements to mitigate this risk. By tackling these issues, our study bridges a significant gap in current research, offering solutions to improve the reliability and efficiency of hydrogen integration into energy systems.

2. Methodology

The PRISMA-2020 methodology [62] was used to collect, analyze, and synthesize evidence on hydrogen blending and injection with natural gas. Fig. 2 shows a schematic flow chart of the review. The review is divided into three parts or PRISMAs: 1) the injection and blending of hydrogen into natural gas pipelines (1 and 2 in Fig. 2); 2) the measurement of hydrogen concentration in pipelines (3 in Fig. 2); and 3) materials to inhibit hydrogen embrittlement (4 in Fig. 2). A preliminary survey was conducted using the Scopus and Web of Science databases, using search terms such as "hydrogen blending in natural gas", "injection" and "static mixers" or "mixing devices" for the 1st PRISMA, "hydrogen sensors or detection or measurement of concentration" for the 2nd PRISMA and "hydrogen embrittlement", "mitigation or coating or permeation or inhibition") in the 3rd PRISMA. A publication interval of 2014–2024 was used to focus on the most recent scientific contributions. To avoid reviewing duplicate papers, a program developed in R was used to remove all duplicate entries from the lists, leaving the final number of papers for screening. In the next step, the titles and abstracts of the papers were screened to filter the most relevant papers that could answer the research question. Eligibility criteria were applied to help filter the full texts.

The 1st PRISMA aimed to review papers focusing on injection and static mixers or mixing devices, with particular attention to flow characteristics, injection configurations, and commercial and non-commercial mixers. The 2nd and 3rd PRISMA, papers were filtered based on high-pressure environments in natural gas transmission pipelines, hydrogen embrittlement, and materials. After appropriate selection, 85 documents were retrieved and categorized as follows: 14 on hydrogen injection and flow conditions (e.g., the effect of temperature and pipeline roughness), 20 on gas/gas flow mixing devices, 27 on hydrogen measurement/detection devices, and 24 on hydrogen embrittlement materials or the main factors influencing material performance in hydrogen environments. In the final stage, the tabulated information was used to identify the main observations on injection system design, flow conditions, instrumentation, and hydrogen embrittlement mitigation, with a discussion section on the main contribution. This work does not cover non-scientific publications, including standards, national policies, and hydrogen programs.

In the subsequent sections, this review first describes the primary hydrogen embrittlement mechanisms and methods for estimating flow homogeneity. Following this, the effects of hydrogen injection, flow conditions, gas mixing, and available technologies for measuring hydrogen concentration in natural gas pipelines are assessed. Additionally, a section is devoted to recent advances in materials designed to inhibit embrittlement. Finally, the discussion section summarizes the main contributions of each part, aiming to support future developments and research.

3. Hydrogen embrittlement description

Under certain conditions, hydrogen injected into natural gas pipelines can cause stratification, with hydrogen rising to the top and methane sinking to the bottom. This stratification can lead to local hydrogen concentration gradients, which can increase the risk of embrittlement. Hydrogen atoms penetrate the surface of the pipeline steel and spread via several pathways, leading to material failure and degradation. As shown schematically in Fig. 3, hydrogen atoms penetrate the surface of the pipeline steel through three main continuous processes [9,59], reducing its ductility and load-bearing capacity, which can lead to cracking and catastrophic brittle failures even under stresses below the material's yield strength [45,63]. Since the H_2 molecules are too large to diffuse through metals, they dissociated into hydrogen atoms on the metal surface and enter the materials by adsorption and absorption (dissolution).

Adsorption involves the interaction between hydrogen gas and metal surfaces and encompasses the mechanisms of physical adsorption (physisorption), and dissociation and chemical adsorption (chemisorption). In physical adsorption (1 in Fig. 3), hydrogen atoms adhere to the metal surface through weak forces like Brownian motion and van der Waals interactions. In chemical adsorption (1 in Fig. 3), hydrogen molecules dissociate and form bonded hydrogen atoms on the surface through stronger, chemical interactions. After adsorption on the metal surface, hydrogen can move into the metal through a surface-subsurface absorption reaction (2 in Fig. 3 - dissolution) [59]. This means that adsorbed hydrogen atoms transition into the bulk of the material and dissolve into the crystal lattice, allowing them to be integrated into the metal structure. Once hydrogen atoms are dissolved in the metal, they diffuse through the material (3 in Fig. 3), moving through interstitial sites and jumping from one site to another. This process is influenced by the temperature, chemical composition, and microstructure of the metal [59].

Materials have imperfections, such as vacancies, dislocations, grain boundaries, solutes, precipitates, inclusions, and interfaces [64]. These act as trap sites for hydrogen atoms, and they can either be reversible or irreversible traps, depending on their binding energy [65]. When hydrogen escapes from reversible traps with low binding energy, it can move through the material and exacerbate issues in areas already cracked, leading to further damage and material failure. On the other hand, irreversible traps have high binding energy, making it difficult for hydrogen to escape. When hydrogen accumulates in these traps, it creates internal stresses that can cause crack formation and weaken the material's structure, making it prone to cracking and eventual failure [63].

Cracks can form and propagate due to several hydrogen embrittlement mechanisms, of which Hydrogen-Enhanced Decohesion (HEDE) and Hydrogen-Enhanced Localized Plasticity (HELP) mechanisms are the most widely recognized and studied mechanisms of HE degradation [45,59,63]. The HEDE mechanism explains that hydrogen weakens atomic bonds at grain boundaries or lattice planes by accumulating in these regions. This segregation reduces the cohesive strength of the metal, leading to intergranular fractures commonly observed in materials susceptible to hydrogen embrittlement. These fractures are typically associated with reduced cohesive interactions and are supported by experimental and theoretical studies [45,66,67]. Meanwhile, the HELP mechanism describes how hydrogen reduces the stress required for dislocation movement, significantly increasing dislocation mobility - up to two to ten times, depending on the material. This increased mobility increases dislocation density, causing dislocations to cluster and lead to premature material failure. Unlike HEDE, fractures caused by HELP are generally ductile due to the localized plastic deformation around the

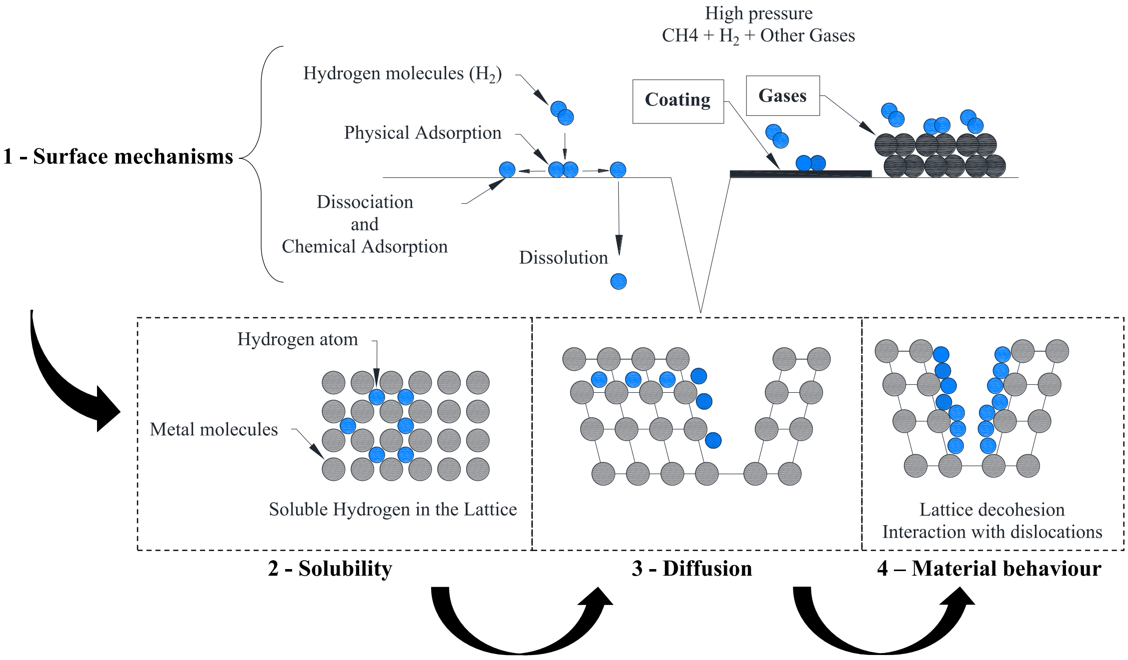

Fig. 3. Schematic illustration of hydrogen embrittlement mechanism.

crack tip [45,68,69]. Hydrogen gathering near dislocations increases local strain, destabilizing the crystal structure. At high enough hydrogen concentrations, this localized deformation can result in a brittle fracture on a macroscopic scale [59].

4. Hydrogen injection and gas flow conditions

In literature, there is a notable scarcity of research on the mixing process and uniformity of hydrogen and natural gas blends. Existing studies are predominantly numerical, focusing mainly on the effects on gas properties and transport processes [70]. The injection placement in the transmission pipeline, injectors geometry, and the momentum ratio are crucial for an efficient blend. Fig. 4 presents schematics of different injection methods described in the literature. In a T-pipe configuration (Fig. 4a), injecting from underneath the pipeline promotes mixing within the flow interior while reducing concentration at the lower surface compared to top-side injection [18]. Another study confirms these findings, showing that perpendicular injection from the side of the pipeline reduces the distance needed to obtain a homogeneous mixture by 3–5 times, while injection from the bottom reduces this distance by around 4 times compared to side injection and 5 times compared to top injection [71]. Moreover, the tube length required to achieve a sufficiently homogeneous gas mixture decreases with increasing inclination angles (Fig. 4b), yielding better results for obtuse angles [72]. The authors consider injection through two symmetrically arranged tubes with varying inclination angles.

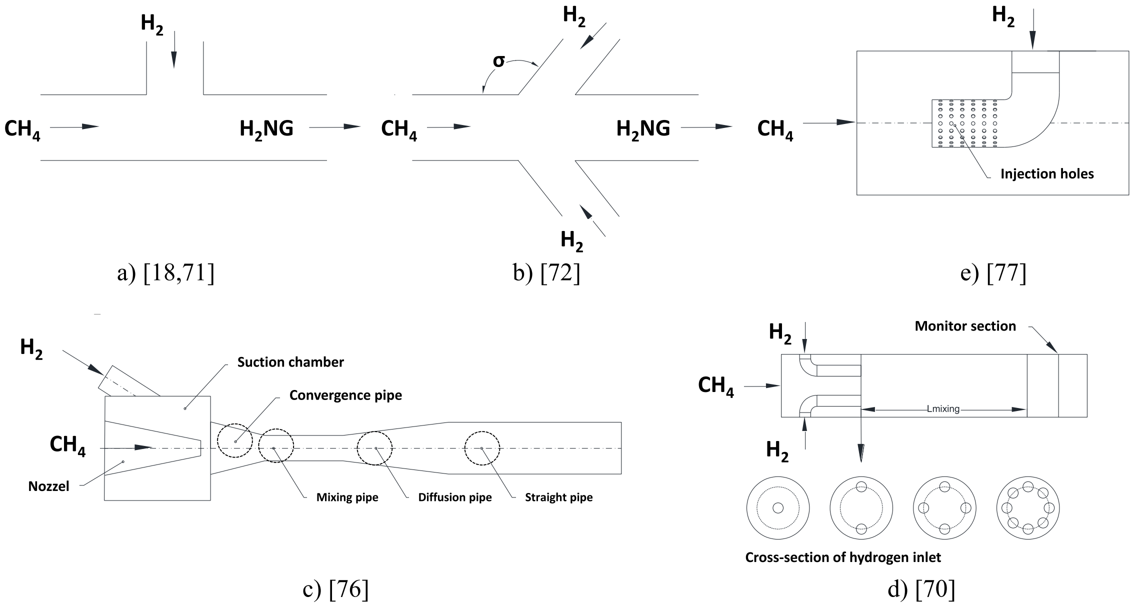

Fig. 4. Schematic representations of different injection configurations.

Increasing the diameter of hydrogen and natural gas pipes or reducing the hydrogen blending ratio will decrease blending efficiency [73]. This effect intensifies at lower velocities, with thresholds contingent on the main pipe diameters. In contrast, Su et al. [74] recommended performing hydrogen injection at low flow rates, high gas temperature, and large pipe diameters to ensure sufficient flow distance for complete gas mixing. Larger diameter pipelines are more energy efficient for hydrogen transport due to reduced frictional drag from a lower surface area to volume ratio [75]. Nevertheless, the occurrence of stratification in T-pipe mixing depends on the momentum of its branches. When the momentum of the hydrogen injection pipeline is high, hydrogen can efficiently penetrate the main flow of natural gas, blending rapidly with it [73]. The momentum ratio of the side pipe to the main pipe should not be lower than 1 [18]. Stratification will occur when the Reynolds number ratio satisfies Re hydrogen $<$ Re nat*ural gas/16* [73]. In situations devoid of stratification, decreasing Re natural gas/Re hydrogen leads to a reduction in the blending distance required for a complete mixture. The above studies focus on a T-tube configuration where the injector geometry is determined by diameter, position, momentum ratio, and inclination angle. However, exploring different injection solutions that enhance mixing is essential for optimizing the blending process.

An et al. [76] investigated the impact of different injector structures on the mixing process (Fig. 4c). The authors proposed an injector where methane flows through a tapering nozzle, converting pressure energy into kinetic energy and creating a high-speed, low-pressure zone that pulls in hydrogen. As the fluids mix and homogenize in a convergent pipe, they form a uniform mixture. Upon reaching a certain pressure level, the mixture exits the injector with superior uniformity compared to the T-pipe configuration. Some authors introduce hydrogen injection through several inlets in natural gas pipelines. Yan et al. [70] studied the effect of several hydrogen injection inlets within a natural gas pipeline (Fig. 4d). Results indicated that increasing the number of hydrogen inlets decreases the distance required for hydrogen and natural gas to mix, although further increases offer diminishing returns. Y. Liu et al. [77] injected hydrogen into natural gas using porous injection (Fig. 4e), employing a pipe with several jet holes inside the pipeline.

In addition to injector designs, the composition of natural gas also impacts the blending process. When natural gas contains more components with higher molecular masses (e.g., heavy hydrocarbons and H_2S), the mixture requires longer distances to blend uniformly. The introduction of hydrogen into natural gas affects several properties of the mixture. Specifically, hydrogen blending decreases natural gas temperature, density, and molar calorific value, while the presence of higher-molar calorific components in imported natural gas leads to an increased molar calorific value post-blending [78]. Unlike many real gases, hydrogen has a negative Joule-Thomson (J-T) coefficient, meaning that a reduction in pressure leads to an increase in temperature. At 7.5 MPa, the J-T coefficient of hydrogen-blended natural gas decreases with rising temperature. Moreover, hydrogen and natural gas have opposing J-T effects, and increasing the hydrogen mixing ratio further reduces the J-T coefficient of the gas mixture [78].

One study investigated the effects of blending hydrogen into natural gas on the inside-valve flow and Joule-Thomson (J-T) characteristics in hydrogen-blended natural gas pipelines. It found that JTCs decrease roughly linearly with increasing hydrogen mole fraction (HMF) from 0 % to 30 %, decreasing by about 30 % and by more than 50 % at HMFs of 15 % and 30 %, respectively [79]. Similarly, numerical work observed that for a hydrogen blending ratio of 30 %, the J-T coefficient of the mixture decreases by 40–50 % compared to natural gas alone. Moreover, the lower the temperature and pressure, the greater the J-T coefficients [80]. The thermodynamic considerations surrounding hydrogen gas flow, such as the challenges posed by compressibility and the energy loss resulting from Joule-Thomson expansion, warrant further investigation [81]. Ignoring this effect, especially under isothermal conditions, can pose challenges such as pressure issues and higher energy consumption during compressor operation [82]. Therefore, careful consideration of the equation of state is crucial, particularly for high-pressure and transient conditions [83].

Table 1 provides a comprehensive overview of the scope, methods, conclusions, and remarks of various studies analyzing hydrogen injection and flow characteristics.

5. Gas mixing

In the literature, the most common method for quantifying gas homogeneity is by using the Coefficient of Variation (COV) of the concentration field across a cross-section. COV can be calculated using Equation (1) considering the gas concentration [77] or Equation (2) considering the velocity field [70].

$$COV = \frac{\sigma}{\overline{c}} = \frac{\sqrt{1 \Big/ A\left(\int_A (c-\overline{c})^2 dA\right)}}{\overline{c}} \tag{1}$$

$$Velocity\_COV = \frac{1}{\overline{v}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(v_i-\overline{v})^2} \tag{2}$$

where σ is the standard deviation, c the volume concentration at the outlet, $\overline{c}$ the volume average concentration at the outlet, A the area of cross-section at the outlet. n is the number of sampling points selected in the cross section, v_i represents the velocity of the monitoring point, and $\overline{v}$ is the average value of the velocity over the monitored section. The COV value ranges from 0 to 1, with lower values indicating more uniform mixing. Mixing can be effective in industrial production applications when the COV value is below 5 % [84]. COV is only an indicator of the variability of the concentration distribution and does not directly correspond to the absolute hydrogen concentration. Achieving such uniform mixtures requires exploring alternatives to simple T-junctions as they do not ensure complete homogenization [85]. Kong et al. [86] demonstrated that in a T-pipe configuration, gases could not fully mix even at 80 diameters. Despite this, with the implementation of a manifold geometry and a SK-Type spiral static mixer, gases mixed within 20 diameters.

Turbulator devices within the pipelines can significantly reduce the distance required for uniform mixing despite increasing pressure drop [70]. Static mixers are used in industry to promote the mixing of fluids, whether they are liquid-liquid, gas-liquid, or liquid-solid mixtures [87]. Commercial static mixers have several advantages, such as: requiring minimal installation space, being low cost, mixing without additional energy costs, lacking moving parts, low maintenance, and offering good mixing efficiency [87]. Therefore, to ensure effective homogenization of the mixer, crucial factors include the maximum safe transport distance, inlet pressure, gas velocity, gas transmission capacity, flow characteristics, ambient temperature, geometric characteristics of the pipeline, economic considerations, technology, and the network design [77].

Several authors have analyzed the mixing performance of gas-gas static mixers. Barrué et al. [88] compared the Oxynator gas-gas mixer with Chemineer (KMA) and Sulzer SMI commercial static mixers under turbulent regimes. The Oxynator prevented gas-wall impact and generated higher turbulence [88], making it more suitable for hydrogen applications. Moreover, non-commercial static mixers also proved to be a good low-cost alternative to commercial ones [89]. The authors compared the performance of two commercial static mixers, the SMV and NOV Kenics, with two new and non-commercial mixers (Screen-Type Static Mixers STSM) featuring divergent inserts of trapezoidal and rectangular shape downstream of a woven mesh. Yang et al. [90] investigated five types of static mixers: traditional, non-aligned, Y-type, double-jet vortex, and new LPD static mixers. Among the mixers, the new LPD static mixer achieved the best mixing effect, while the Y-type static mixer performed the worst. In another study, some

Table 1
Overview of hydrogen injection and flow characteristics.

Reference	Scope	Method	Remarks
[18]	T-Joint injection geometry (diameter ratio, various 90° orientations) and hydrogen injection ratio (4.8–20%vol)	CFD	The momentum ratio of the side pipe to the main pipe should be > 1. Injection from the under-side of the pipeline enhances mixing.
[71]	T-joints injection considering ideal and soave-redlich-kwong real gas models	CFD	Side injection reduces distance by 3–5 times; bottom injection by 4 times compared to side and 5 times compared to top.
[72]	Gas mixing using a multi-injection system with varying angles of inclination and inflow conditions	CFD	Obtuse inclination angles decrease the distance needed for uniform mixing.
[73]	Flow characteristics in a T-pipe (velocity of main pipe, hydrogen ratio, diameters) using large eddy Simulation	CFD	As hydrogen mixing ratio decreases and hydrogen injection pipe and main pipe diameters increase, the distance required for uniform mixing downstream also increases. Stratification occurs when Reynolds number of hydrogen Re_{H2} < than natural gas Red_{NG}/16.
[76]	Study of multiple structural parameters of injectors	CFD	The proposed injector configuration achieves blend uniformity 10 times greater than that of a T-pipe configuration.
[70]	Number of injectors and their position	CFD	Increasing the number of injectors reduces the distance to a uniform mixing while increase for higher hydrogen mixing ratios
[74]	Investigated the hydrogen injection in a T-junction natural gas pipeline	CFD/Deep neural Network model	Mixing becomes increasingly uniform with greater flow distance, higher gas temperature, hydrogen blending ratio, and larger pipeline diameter ratios. Lower gas velocity enhances mixing uniformity.
[75]	Effects of pipe roughness, pipe diameter, and pipe bends	CFD	Larger roughness increases energy requirements due to higher frictional effects compared to smoother surfaces. Larger diameters are more energy-efficient due to lower surface area-to-volume ratio, reducing frictional drag along the inner pipe surface. Bends introduce additional energy penalties, emphasizing the importance of minimizing bends in hydrogen gas network design to reduce transportation costs.
[78]	Transport and thermodynamic properties of imported natural gas injected with hydrogen	CFD	Natural gas with higher molecular mass components requires longer distances for uniform blending. At 7.5 MPa, J-T coefficient of the blend decreases with the increase of temperature. Hydrogen and natural gas exhibit opposing joule-thomson effects. Mixing hydrogen decreases the joule-thomson coefficient of natural gas, gradually reducing it as the hydrogen mixing ratio increases.
[80]	Effect on J-T coefficient of Natural Gas	Numerical model	When the hydrogen blending ratio reaches 30%, the J-T coefficient of the mixture decreases by 40–50% compared to natural gas.
[79]	Effects on joule-thomson	CFD	J-T coefficient decreases linearly with the increase of hydrogen fraction. The lower the temperature and pressure, the greater the J-T.

multifunctional static mixer technologies for different fluids and qualitative and quantitative methods for measuring mixtures were presented. The authors remark Sulzer's SMV, Ozone Mixer, and Komax Systems for gas-gas mixing, which may potentially be used for H_2NG blending [91].

The mixing pattern is influenced by the geometric features of the mixers [92]. One study experimentally examined the heat transfer enhancement in a tube fitted with a Koflo Blade™ inline mixer, finding that that mixer with a clamp angle of 120° was more effective [93]. Yang et al. [90] study showed that mixing uniformity improved as the torsion angle and number of elements increased and as the aspect ratio decreased. Torsion angle had the most significant effect on mixing performance. Kong et al. [94] demonstrated that three helical static mixer elements optimize hydrogen-natural gas mixing, with a 120° torsion angle minimizing the coefficient of variation and reducing pressure loss. Consecutive unit arrangements proved the most effective. Y. Liu et al. [77] found that four SMX static mixer elements optimize hydrogen-natural gas blending. Both pressure drop and COV increase with inlet gas velocity, but COV rises less. An optimal gas velocity of 10 m/s was identified. Moreover, increased hydrogen fraction leads to increased pressure drop and decreased COV, indicating improved mixing. Zheng et al. [95] explored alternatives to the SMX mixer by developing a coaxial shear static mixer with annular structures, which showed significant advantages over the SMX in terms of mixing uniformity and pressure loss. The coaxial shear mixer achieved a uniformity of 95.43% (compared to 95% for the SMX) and a significantly lower pressure drop of 67.02 Pa compared to 500 Pa for the SMX. Di et al. [96] investigated a novel static mixer design featuring four trapezoidal baffles arranged in a circular pattern, with adjacent elements staggered. Their study found that optimal mixing performance was achieved when the mixer was installed 3D downstream of the blending point, with a spacing of 1D between elements and four mixing elements used.

Liu et al. [97] studied different geometric configurations such as "S" bends, pipe reducers, orifice plates, and spiral vane mixers (SVM) with similar geometry in Kong et al. [86] work. "S" bends improved mixing with smaller radii but were limited by size, cost, and a 42D blending distance. Reducers were less efficient with longer lengths and larger diameters, needing 6D. Orifice plates are efficient with smaller diameters and fewer holes, mixed at 5D. Spiral mixers, effective at 1D, improved with higher blade angles but worsened with longer lengths, making them a preferred choice for their simplicity and cost-efficiency.

Static mixers were tested across different velocities (0.5–20 m/s) and hydrogen volume fractions (5–20 % mol). The KVM static mixer consistently homogenized within 7 diameters, while the helicoidal mixer (KMS) did so within 13 diameters but with increased pressure loss. The influence of hydrogen volume fraction on homogenization was sharper without a static mixer than with one. Nonetheless, static mixers like the KVM are recommended for effective homogenization in natural gas pipelines despite the associated pressure loss, which should be compensated for by additional energy from compressors [85].

The configuration of the pipeline network setup also affects the mixture. One study analyzes hydrogen injection into a natural gas pipeline. The setup involved a mixing station with separate gas lines for H_2, CH_4, CO_2, and H_2S, leading to a reservoir and subsequent injection into the pipeline. The study aimed to determine the need for a static mixer for homogeneous mixing. It concluded that a static mixer was unnecessary due to good mixing quality [98].

The development of a mixing system can prevent the stratification of hydrogen inside the pipeline. However, to maintain the uniformity of the mixture, it is necessary to keep the flow in a turbulent regime [18]. If the flow becomes laminar or stagnant, such as in the pipes of the gas distribution network, stratification can occur due to differences in density [18]. For instance, C. Liu et al. [99] found that when the shut-off valve was activated, causing stagnation, stratification occurred and stabilized over time. Stratification can also occur in pipelines with risers. Villuendas et al. [98] observed post-expansion flow asymmetries from DN 80 to DN 250, extending 0.5 m downstream, with fully developed flow achieved around 20 diameters downstream. Real-time monitoring of the gas concentration within the pipelines is crucial to prevent HE and control the flow conditions.

Table 2 summarizes key studies on hydrogen mixing devices, highlighting the scope, the methods, conclusions, and specific remarks regarding the performance and applicability of various static mixers in hydrogen-natural gas blending scenarios. The results underscore the significance of selecting appropriate mixer designs and configurations to achieve uniform mixing, minimize pressure loss, and maintain system efficiency.

6. H_2NG concentration measuring

Literature reveals a significant gap in experimental validation for the numerical models. Su et al. [74] highlighted the limitations in placing sensors to measure the gas concentration across the pipeline's cross-section as a challenge. When injecting hydrogen into the natural gas network, it is important to monitor gas composition at various locations [100]: 1) at the injection point into the network, to ensure the desired hydrogen percentage; 2) within the distribution network, for quality control and potential future energy billing considerations; 3) during hydrogen/natural gas separation, to ensure the quality of pure hydrogen or natural gas; and 4) at the industrial end-user sites, for quality control purposes. Measuring gas concentrations is crucial as it enables the calculation of the COV, helping prevent hydrogen stratification and potentially serving as input for control systems (injection flows and pressure, ratios, etc.). The most common method for determining gas concentration is through chromatography. Chromatographers can detect hydrogen gas [77,101], usually by using a thermal conductivity detector and helium as the carrier gas instead of hydrogen [102,103]. For example, in the work of Y. Liu et al. [77], gas samples were collected at radial points within the pipeline to measure the mixing uniformity. However, chromatography is expensive, does not allow for

Table 2
Comparative overview of hydrogen mixing devices.

Reference	Scope	Method	Remarks
[88]	Mixing performance of three static mixers: Oxynator, KMA and SMI	Experimental (laser Doppler anemometry)	Oxynator static meter prevents gas-wall impact, generates high turbulence and has low mixing distance suitable for hydrogen.
[86]	Mixing process of natural gas with different components in manifold and T-pipe, and manifold with SK-Type static mixer	CFD	The T-pipe configuration fails to fully mix the gases. Manifold and manifold with static mixer can mix gas at 55D and 20D, respectivily.
[89]	Mixing performance of two commercial static mixers (SMV, KOV kenics) with two non-commercial mixers	CFD	Combination of screen-type static mixers with divergent inserts offers a good alternative for commercial designs.
[93]	Performance of a mixer (koflo Blade™ inline mixer) having 90° and 120° blades crossing angles	Experimental	Mixer with a 120° clamp angle was more effective.
[90]	Performance of five static mixers: traditional, non-aligned, Y-type, double-jet vortex, and LPD.	CFD	The LPD static mixer performed best, while the Y-type static mixer performed worst.
[91]	Overview of static mixers technologies	Review	Sulzer's SMV, ozone mixer and komax Systems' gas/gas mixers recommended designs.
[94]	Effect of a helical static mixer on hydrogen-natural gas mixing	CFD	Three mixing elements provide efficient performance with good compromise between pressure loss and COV; a torsion angle of 120° gives the lowest COV; a consecutive arrangement of mixing units is most suitable.
[77]	Hydrogen blending using a SMX static mixer	CFD/ Experimental	Four mixing elements balance pressure drop and COV; Both pressure drop and COV increase with inlet velocity, but COV rises less significantly. The optimal velocity is 10 m/s; higher hydrogen fraction increases pressure drop but reduces COV.
[95]	Effect of a coaxial shear static mixer with annular structures	CFD	Uniformity of 95.43% (compared to 95% for SMX) and a pressure loss of 67.02 Pa (much lower than 500 Pa for SMX).
[96]	Effect of a novel static mixer design with four trapezoidal baffles arranged in a circular pattern	CFD	Optimal mixing when the mixer was installed 3D downstream of the blending point, with 1D spacing between four elements.
[70]	Effect of injection points and use of a turbulator device	CFD	Turbulators decrease the distance to get uniformity but increase the pressure drop.
[97]	Effect of "S" blends, a pipe reducer, an	CFD	SVM mixer is the preferred choice due to its simplicity, cost-

(continued on next page)

Table 2 (*continued*)

Reference	Scope	Method	Remarks
	orifice plate and SVM mixer		efficiency and superior mixing performance.
[18,99]	Gas stratification after mixing device	CFD	Flow should be kept in turbulent conditions; stagnation may induce gas stratification over time.
[98]	Simulation of H_2NG mixing in a setup with the main characteristics of injection sites and gas pipelines of the transmission gas network	CFD/ Experimental	Static mixer was unnecessary due to good mixing quality achieved with four individual gas lines. Flow asymmetries were observed when DN80 to DN250 but rapidly uniform 20 diameters downstream.
[85]	Alternative to T-Junction using static mixers	CFD	T-Joint couldn't ensure full homogenization. The KVM static mixer consistently homogenized within 7 diameters, while the helicoidal mixer did so within 13 diameters but with increased pressure loss. KMV has a lower pressure drop.

real-time information, and can be inaccurate in more complex cases [104]. Moreover, this analysis typically occurs at a standard pressure of 1 atm, which does not accurately represent the pressure conditions found in gas pipelines.

Another method for assessing the homogeneity of the mixtures is the Particle Image Velocimetry (PIV) [84]. This optical method provides a visual and quantitative analysis of flow patterns using tracer particles. It renders relevant results that can be qualitatively compared with CFD models. Similarly, techniques like laser velocimetry and hot wire anemometry allow quantitative analysis of flow velocities at any point, while mixing efficiency is characterized by laser sheet visualizations [88]. Introducing a laser sheet into the injected gas flow along with a few droplets enables the visualization of droplet distribution within a section of the tube. Homogeneity is assumed when no differences in droplet density are observed within the measurement section. While this visual observation does not provide a quantitative value of the mixture and thus does not allow for the calculation of the standard deviation, it does enable the identification of areas with high and low tracer concentrations. This helps in understanding the mixing mechanisms and comparing different sections and types of mixing systems, assuming consistent observation.

While infrared (IR) spectroscopy is effective for analyzing natural gas composition, it struggles to measure molecules like hydrogen due to their symmetric structures. On the other hand, Raman spectroscopy shows promise of detecting hydrogen directly and the composition of natural gas in real-time [105,106]. However, this method is costly and cannot analyze hydrogen stratification, which is crucial for preventing embrittlement. High-pressure nuclear magnetic resonance (NMR) spectroscopy can quantify the composition of natural gas and hydrogen [107–110], but it requires dedicated facilities, experienced user, and is very expensive [111]. Recently, Restrepo et al. [111] introduced a cost-effective methodology using high-pressure proton NMR spectroscopy for analyzing hydrogen-enriched natural gas (HENG) composition up to 245 bar. Their approach featured a simple flow-through cell design and improved spectral quality and stability compared to previous methods [112–114]. It accurately determines H_2NG blend compositions and allows real-time monitoring of hydrogen buoyancy.

While there are sensors available on the market capable of measuring and controlling hydrogen levels, reliable technology for accurately measuring the composition and calorific value of the mixtures is still lacking [100]. Hall et al. [115] and more recently, Wang et al. [116] summarized some gas sensors capable of measuring hydrogen presence. In the literature review, solutions for smaller sensors based on material interactions between hydrogen and active materials, such as metals, metal oxides, or other nano-materials, have been proposed [117–120]. Most commercial sensors are of the catalytic type, conductometric sensors based on semiconducting metal oxides, and electrochemical sensors [121]. However, these sensors are primarily used to detect hydrogen leaks and in the presence of oxygen [121].

Nonetheless, Occelli et al. [121] point out that all these sensors do not allow for the analysis of H_2NG mixtures inside the pipeline in a completely anaerobic and dry environment. Buttner et al. [122] identified thermal conductivity (TC) and Palladium thin film (PTF) sensors as the most promising for such anaerobic environments. The former measures the heat loss of a hot body exposed to the environment. However, TC gas sensors, while sensitive to hydrogen and nitrogen, are unsuitable for accurate hydrogen measurement in natural gas environments due to baseline drift caused by changes in gas composition. The latter measures the variation in the physical properties of the thin film (conductivity, optical index) due to the reaction of H_2 with palladium, which leads to the formation of hydrides [121]. However, both methods operate at atmospheric pressure, necessitating a secondary loop to transfer the pressurized gaseous mixture from the pipeline into a chamber for sample collection and analysis.

Table 3 outline the various techniques used for measuring gas compositions, particularly in the context of hydrogen-natural gas mixtures, highlighting their capabilities and limitations.

7. Factors shaping material performance in hydrogen environments

Pipelines in high-pressure grids primarily consist of carbon high-grade steels, which are susceptible to hydrogen embrittlement. The risk of embrittlement depends on several factors, including the quality of the steel (e.g. microstructure), the conditions to which the material has been exposed [123], the method of hydrogen entry, and charging times [124]. The composition and microstructure of a material are essential in determining its resistance to hydrogen embrittlement. However, there are contradictory statements in the literature regarding the sensitivity of high-grade steels to hydrogen embrittlement. Wei et al. [125] found that hydrogen has minimal impact on the strength of X80 pipeline steel but significantly affects elongation, fracture toughness, and fatigue crack growth rate when mixed with natural gas up to 15 vol % hydrogen at 12 MPa total pressure. Cao [126] found that longer charging times increased yield and ultimate strengths but decreased tensile elongation and impact energy of L245 steel. Contrastingly, one research that investigated the tolerance of the most typical material pipelines and key elements of 20 mol % hydrogen blends at 80 bar for 3000 h using a pilot installation showed no embrittlement or other kind of damage to valves or the different parts of the equipment (regulator, flowmeter) tested. Additionally, specimens made from carbon steel pipes did not show any damage after exposure to hydrogen [123]. Similarly, Hafsi et al. [127] found that injecting hydrogen up to approximately 30 % is safe, preventing pipeline (X52 steel) failure due to internal stress.

The microstructure of a material can influence its susceptibility to HE [128,129], with the base metal affected more in tensile properties and weld joints more vulnerable in impact properties. Kappes and Perez [54] highlighted the higher risks near welds, underscoring the importance of investigative the microstructure in pipeline materials. The alloy composition of steels can influence their resistance to HE. A study evaluating the HE resistance of four face-centered cubic concentrated solid solution alloys and found that the presence of iron and chromium effectively reduced the HE behavior while manganese increased it. The study also suggested that the susceptibility of a material to HE is heavily influenced by the concentration of deuterium, determined by both the

Table 3
Resume of the different techniques to measure hydrogen blend natural gas concentration.

Method	High pressure	Gas composition	Gas stratification	Real Time	Notes
Chromatography	×	✓	✓	×	Can easily detect hydrogen. Complex and sometimes inaccurate. Expensive.
Particle image velocimetry	✓	×	✓	×	Allow the flow pattern to be visualized. Provides qualitative analyses.
Laser velocimetry and hot wire anemometry	✓	×	✓	×	Measures flow velocity at specific points. Understand the tracer concentrations in a section Cannot provide quantitative mixture results or calculate standard deviation. s
Infrared (IR) spectroscopy	✓	×	✓	×	Effective for analyzing natural gas composition. Struggles to measure molecules like hydrogen due to their symmetric structures.
Raman spectroscopy	✓	✓	×	✓	Detect hydrogen directly and the composition of natural gas and in real time. Costly and cannot analyze hydrogen stratification, which crucial for preventing embrittlement.
High pressure nuclear magnetic resonance (NMR) spectroscopy	✓	✓	✓	✓	Can quantify the composition of natural gas and hydrogen. Requires dedicated facilities and experienced users, and is very expensive
Proton NMR spectroscopy for analyzing hydrogen-enriched natural gas	✓	✓	✓	✓	Accurately determines H_2NG blend compositions and monitors hydrogen buoyancy in real-time.
Hydrogen sensors detection	×	×	✓	✓	Work in the presence of oxygen, not allowing to analyze H2NG mixtures with a completely anaerobic environment. Palladium thin film sensors are the most promising but operate at atmospheric pressure. Thermal conductivity gas sensors are unsuitable for accurate hydrogen measurement in natural gas environments whenever there is a change in gas composition other than H_2 or N_2.

constituent elements of the material and the duration of hydrogen exposure [130].

Environmental factors, such as temperature, influence hydrogen diffusivity and concentration in steel. Xu et al. [131] found that in the temperature range of 20 °C–60 °C, hydrogen diffusivity in X52 steel notably rises with increasing temperature. As temperature increases, subsurface hydrogen concentration decreases due to faster hydrogen diffusion relative to absorption. Their findings indicate an elevated susceptibility to hydrogen embrittlement in X52 steel at higher temperatures [131]. Also, another study, confirming the results of a previous one, concluded that hydrogen diffusion coefficient and subsurface hydrogen concentration exhibited a systematic increase with increasing temperature over the range of 26.85 °C to 51.85 °C. The experimental results suggested the temperature threshold of HE being at 41.85 °C (315 K), where brittle patterns featured by quasi-cleavage planes and secondary cracks were observed [132].

Furthermore, the HE is also impacted by factors like the concentration and partial pressure of hydrogen and gas mixers compositions. The presence of carbon monoxide (CO) in high-pressure hydrogen gas decreases gaseous hydrogen permeation current density and subsurface hydrogen concentration while increasing fracture strain and reducing the HE index of X52 steel. This effect is amplified with higher CO partial pressure, suggesting that CO enhances steel's resistance to HE in gaseous hydrogen environments [133]. Similarly, R. Zhang et al. [134] demonstrated that CO/CO_2 inhibits HE, with CO showing a more effective inhibitory effect. Zhao et al. [135] and C. Liu et al. [136] found that for steel X80, the HE index decreased with increased CO or CO/H_2 and then stabilized. CO occupies hydrogen adsorption sites in the presence of H_2, reducing but not fully inhibiting hydrogen permeation, which explains the impact of CO concentration on HE susceptibility. Additionally, CH_4 can reduce the HE index by 11% at a CH_4 content of 20 vol %, while CO provides good protection starting at 0.1 vol % and peaking at 5 vol % [136]. In their review paper, Wang et al. [137] emphasized that introducing gases like O_2 and CO has the potential to inhibit hydrogen embrittlement, suggesting a promising solution for high-pressure hydrogen pipelines if their effectiveness is proven universally across various steel grades.

Surface coatings and treatments have proven to be viable solutions for reducing the susceptibility of materials to hydrogen embrittlement [138]. The use of $Fe_xAl_y/Al/Al_2O_3$ composite coating, doped with La_2O_3 and Ce_2O_3 on the surface of X80, significantly improved the hydrogen barrier properties [139]. Polyvinyl alcohol (PVA) and poly (ethylene glycol) diglycidyl ether (PEGDGE) crosslinked polymer materials for internal coatings can significantly reduce hydrogen permeation to steel surfaces [140]. Furthermore, these materials exhibit shear-thinning and thixotropic behavior, enabling easy on-site application to existing infrastructure. They achieved a hydrogen permeability of 0.01 Barrer, 100 times lower than commercially available coatings. Mathematical modeling shows that a 1 mm crosslinked PVA coating can extend hydrogen equilibrium to two years and reduce steel hydrogen levels. A 2 mm coating can extend this to seven years with a 44% reduction, and a 10-fold decrease in diffusivity can extend it to eight years, reducing surface hydrogen by 84% [141].

Results from Xu et al. [142] show that the presence of $FeCO_3$ scales significantly reduces hydrogen permeation flux, effective diffusion coefficient, and subsurface hydrogen concentration, suggesting inhibition of hydrogen permeation and embrittlement susceptibility in X52 steel. $FeCO_3$(104) surfaces show less favorable hydrogen adsorption when compared to Fe (100) surfaces, hindering hydrogen permeation overall and acting as barriers in gaseous environments. One study proposed a low-cost laminated metal composite consisting of an austenitic stainless-steel layer and a martensitic steel layer, offering high mechanical strength and excellent resistance to HE. This design achieved an ultimate strength of approximately 1.1 GPa and elastic modulus loss below 15 % after hydrogen charging with sides sealed [143]. Existing coatings are difficult to apply to pipelines due to complex structures and harsh operating conditions [144]. Research by Zu et al. [144] showed that the epoxy coating could reduce hydrogen embrittlement in X80 pipeline steel by over 35% and prevent embrittlement at hydrogen partial pressures below 3 MPa, thereby increasing the steel's resistance to hydrogen-blended natural gas transport. Another recent study demonstrated the potential of tungsten disulfide composite coatings on X70 steel, showing improved resistance to hydrogen permeation and embrittlement [145].

The use of coatings has shown promising results. However, careful selection is crucial due to the potential for coating materials, such as palladium, to exacerbate internal stress and strain changes induced by hydrogen in steel [124]. In addition to steel, rubber sealing materials can also suffer from hydrogen damage due to hydrogen permeation, thus seriously affecting the reliability, stability, and safety of high-pressure hydrogen systems [146]. Strategies for enhancing hydrogen barrier properties include increasing material polarity, using fillers with high surface area, and applying hydrogen barrier coatings. It is important to continue developing new solutions and tolls, which may aid in the material design of pipelines and ensure that fracture propagation can be arrested in case of an accident [147].

Table 4 encapsulates an overview of factors influencing material performance, highlighting ongoing research and practical solutions aimed at mitigating HE in pipelines and other critical components. This research overview indicates a concerted effort towards ensuring the structural integrity and safety of high-pressure hydrogen systems.

Table 4

Overview of factors influencing material performance.

Reference	Scope	Method	Remarks
[125]	Effect on mechanical properties of X80 steel	Experimental	Affects elongation, fracture toughness, and fatigue crack growth rate for H_2 up to 15 vol% at 12 MPa. Fracture toughness creases up to 61.98%.
[126]	Effect in tensile properties and weld joints	Experimental	HE affects base metal more in tensile properties and weld joint more in impact properties.
[54]	Review of HE, governing codes, and life prediction methods	Review	The work highlighted elevated risks near welds.
[123]	Impact on materials and equipament for 20 mol% hydrogen blends at 80 bar for 3000 h	Experimental	No embrittlement or other kind of damage to valves or the different parts of the equipment.
[131]	Temperature effect on HE at 20 to 60 °C in X52 steel	Experiments	Elevated susceptibility to hydrogen embrittlement in X52 steel at higher temperatures.
[132]	Effect of temperature in HE between 26.85 °C and 51.85 °C	Experimental	Hydrogen diffusion coefficient/subsurface hydrogen concentration increase with increasing temperature. Temperature threshold of HE being 41.85 °C (315 K).
[133]	Effect of CO	Experimental	CO enhances the steel's resistance to hydrogen embrittlement in X52 Steel.
[134]	Effect of natural gas impurities	Experimental	CO/CO_2 inhibits HE, with the inhibitory effect.
[135]	Effect of CO	Experimental	That HE index decreased with the increase of CO or CO/H2, then stabilized. CO does not completely inhibit hydrogen permeation.
[127]	Effect of upstream hydrogen injection on the structural integrity of pipelines	Numerical	Transient pressure oscillations may lead to embrittlement; injecting hydrogen up to approximately 30% is safe, preventing pipeline (X52 steel) failure due to internal stress.
[147]	CFD model to predict the decompression wave speed of the mixture	CFD	Model can help in the material design of pipelines to ensure that fracture propagation can be arrested.
[136]	Effects of CH_4 and CO (X80 steel)	Experimental	CH4 could reduce HE index till reaching about 11% with a CH4 content of 20 vol%, and CO could prevent HE, providing good protection at 0.1 vol% and peaking at 5 vol%.
[137]	Hydrogen compatibility of pipelines	Review	Introducing gases like O_2 and CO has the potential to inhibit

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8. Discussion and main conclusions

The blending and injection of hydrogen into natural gas networks has seen significant advancements yet continues to face challenges. Hydrogen blending is a promising strategy for reducing carbon emissions by leveraging existing natural gas infrastructure. However, several complexities arise due to the unique physical properties of hydrogen that may lead to material embrittlement. The research underscores the importance of injection methods in achieving effective hydrogen-natural gas mixtures. Studies demonstrate the superiority of perpendicular and bottom-side injections over top-side methods [18,71]. Additionally, obtuse inclination angles and larger pipe diameters can enhance mixing efficiency by decreasing the required downstream distance for uniform blending [72,73].

Static mixers are crucial for ensuring the homogeneity of hydrogen-natural gas blends. The combined use of static mixers and injection systems has shown significant improvements in blending uniformity over traditional T-pipe configurations [85,86]. The mixer geometry plays an important role concerning the mixing efficiency, with helical static mixers with a torsion angle of 120° providing an efficient balance between pressure drop and COV [93,94]. Additionally, combining multiple mixing elements and specific configurations can enhance performance while managing pressure drops effectively. Non-commercial mixers, such as scree-type static mixers with divergent inserts, offer a promising alternative [89].

Even though gases are blended, accurate and real-time monitoring of hydrogen concentrations is crucial for ensuring the safety and efficiency of hydrogen-natural gas blends. Several techniques, including chromatography, infrared spectroscopy, and NMR spectroscopy, have been evaluated for effectiveness. While methods like Raman spectroscopy and proton NMR spectroscopy provide real-time and accurate measurements [107–110], they are often costly and require specialized facilities and expertise. However, a cost-effective proton NMR spectroscope was developed for high-pressure environments (245 bar) [111]. Hydrogen sensors, particularly palladium thin film sensors, offer promising results but are limited to atmospheric pressure environments [122]. Therefore, developing more versatile and cost-effective sensors for high-pressure applications remains a critical area for future research.

Hydrogen embrittlement remains a significant challenge for the integration of hydrogen into natural gas pipelines. This phenomenon adversely affects mechanical properties such as elongation, fracture toughness, and fatigue crack growth rate, particularly in high-pressure environments [125,126] and elevated temperatures [131,132]. Certain impurities in natural gas, such as CO and CO_2, or O_2 and components such as iron, chromium, and $FeCO_3$ can inhibit hydrogen embrittlement [130,133,134,137,142]. Protective coatings and advanced alloys are essential for mitigating HE. The use of composite coatings doped with La_2O_3 and Ce_2O_3 has been shown to significantly reduce HE [139]. Finally, crosslinked PVA-based polymer coatings and laminated metal composites consisting of austenitic and martensitic

Table 4 (*continued*)

Reference	Scope	Method	Remarks
			hydrogen embrittlement.
[139]	Fe$_x$Al$_y$/Al/Al$_2$O$_3$ composite coating doped with La$_2$O$_3$ and Ce$_2$O$_3$ on the surface of X80	Experimental	Composite coating significantly improved the hydrogen barrier properties of X80 steel.
[124]	Influence of hydrogen on residual stresss and strain, influence of coating	Experimental	Coating materials like palladium may exacerbate the internal stress and strain changes induced by hydrogen in the steel.
[138]	Insights into safety, corrosion, HE, coating and linings	Review	Coating and lining materials are a viable solution.
[130]	HE resistance of four face-centered cubic concentrated solid solution alloys	Experimental	The presence of iron (Fe) and chromium (cr) effectively reduced HE behavior, while manganese (Mn) increased it.
[130,140]	Crosslinked PVA based polymer coatings	Experimental/ Mathematical modeling	Polyvinyl alcohol (PVA) and poly (ethylene glycol) diglycidyl ether (PEGDGE) crosslinked polymer materials for internal coatings can significantly reduce hydrogen permeation. Hydrogen permeability of 0.01 barrer.
[143]	Proposed a low-cost laminated metal composite consisting of austenitic stainless steel layer and martensitic steel layer	Experimental	Offers high mechanical strength and excellent resistance to HE. This design achieves an ultimate strength of approximately 1.1 GPa and elastic modulus loss below 15% after hydrogen charging with sides sealed.
[144]	Effect of epoxy coating on the surface of X80 steel	Experimental/ Simulation	The epoxy coating reduced hydrogen embrittlement by over 35% in X80 pipeline steel and prevented embrittlement at hydrogen partial pressures below 3 MPa.
[142]	Effect of FeCO$_3$ corrosion product	Experimental	The presence of FeCO$_3$ scales significantly reduces hydrogen permeation flux, effective diffusion coefficient, and subsurface hydrogen concentration, suggesting inhibition of hydrogen permeation and embrittlement susceptibility in X52 steel.
[146]	Rubber sealing materials	Experimental	Hydrogen barrier properties of rubber materials can be achieved by increasing the polarity of the material, filling with high surface area fillers, and constructing hydrogen barrier coatings.

steel layers offer promising solutions for reducing hydrogen permeation and enhancing mechanical strength [140,143].

While the literature provides valuable insights into injection, mixing, instrumentation, and materials, significant research gaps remain.

- Although numerical studies provide valuable insights, further experimental research is essential to validate and complement these findings. The lack of experimental validation often leads to discrepancies with real-world conditions, especially in complex, high-pressure environments. Experimental work is needed to verify boundary conditions, numerical methods, and turbulence models to improve accuracy.
- Injection systems must go beyond merely delivering pure hydrogen to effectively blending the gases before injecting them into main natural gas pipelines. This process enhances inertia and momentum, promoting efficient mixing and reducing the risk of stratification.
- Real-time gas concentration measurements present a significant challenge but are crucial for controlling hydrogen stratification across pipeline sections. Investigating new technologies capable of operating in anaerobic, high-pressure conditions or using parallel networks for atmospheric pressure measurements is warranted to address this challenge effectively. In addition, the gas concentration measurements are essential for the researchers to validate their numerical models, which is one of the main limitations of the experimental work.
- There is a notable gap in the literature concerning the development and application of new coating solutions for mitigating hydrogen embrittlement in operating pipelines. Further research into the effectiveness and applicability of these coatings, as well as the impact of blending various gas compositions to enhance hydrogen diffusivity in steel, is essential for ensuring pipeline integrity and safety.

Addressing these research gaps and challenges will be crucial for advancing our understanding of hydrogen injection into natural gas pipelines and developing effective strategies to ensure the safety, reliability, and efficiency of hydrogen transport infrastructure. Collaboration between researchers, industry stakeholders, and policymakers will be essential to drive progress in this field.

CRediT authorship contribution statement

Nuno Rosa: Writing – original draft, Methodology, Investigation, Conceptualization. **Nazanin Azimi Fereidani:** Writing – review & editing, Methodology. **Bruno J. Cardoso:** Writing – review & editing. **Nuno Martinho:** Writing – review & editing. **Adélio Gaspar:** Writing – review & editing. **Manuel Gameiro da Silva:** Writing – review & editing.

Data availability

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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