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Review article

Study progress on the pipeline transportation safety of hydrogen-blended natural gas

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ABSTRACT

The core of carbon neutrality is the energy structure adjustment and economic structure transformation. Hydrogen energy, as a kind of clean energy with great potential, has provided important support for the implementation of the carbon peaking and carbon neutrality goals of China. How to achieve the large-range, safe, and reliable transportation of hydrogen energy with good economic benefits remains the key to limiting the development of hydrogen energy. Using the existing natural gas pipeline network can save many infrastructure construction costs to transport hydrogen-blended natural gas. However, due to great differences in the physical and chemical properties of hydrogen and natural gas, the transportation of hydrogen-blended natural gas will bring safety risks to the pipeline network operation to a certain extent. In this paper, the influences of pipeline transportation of hydrogen-blended natural gas on existing pipelines and parts along the pipelines are analyzed from two aspects of pipe compatibility and hydrogen blending ratio, and the safety of pipeline transportation of hydrogen-blended natural gas is summarized from two aspects of leakage and accumulation as well as combustion and explosion. In addition, the integrity management of hydrogen-blended natural gas pipelines and the existing relevant standards and specifications are reviewed. This paper points out the shortcomings of current hydrogen-blended natural gas pipeline transportation and gives some relevant suggestions. Hopefully, this work can provide a useful reference for developing a hydrogen-blended natural gas pipeline transportation system.

1. Introduction

Due to the rapid development of the global economy and society and the rapid increase in energy consumption, traditional fossil energy reserves such as coal, oil, and natural gas have been greatly reduced, and the greenhouse effect and environmental pollution have become increasingly serious. Therefore, all parties in the world today are trying to find clean, low-carbon, and developable new energies as an alternative to meet current challenges. As a renewable resource, hydrogen energy has the advantages of clean, zero carbon emission, no harm, high energy storage density, rich resources, and a wide range of application forms [1–3]. Hydrogen energy has been rated “the most ideal new energy in the 21st century” and has huge application potential [4,5]. However, due to the very small density and the flammable and explosive characteristics of hydrogen at normal temperature and pressure, achieving safe, reliable, economical, and efficient transportation of hydrogen energy is challenging [6].

Hydrogen energy transportation technology can be divided into high-pressure gaseous hydrogen transportation, low-temperature

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liquid hydrogen transportation, solid material hydrogen transportation, organic liquid hydrogen transportation, and hydrogen blended natural gas pipeline transportation [7]. From the perspective of large-scale and long-term development of hydrogen energy, the transportation modes of high-pressure gaseous hydrogen and low-temperature liquid hydrogen have high costs and low efficiency. Hence, they cannot meet the requirements of large-scale regional coverage of hydrogen energy. Pipeline hydrogen-blended transportation will become the inevitable trend of future development. Although pure hydrogen pipeline transportation has been applied in some countries, it cannot meet the needs of hydrogen energy development because of its high cost. The most reasonable solution for the future cost-effective, large-scale, and sustainable hydrogen energy supply is hydrogen-blended natural gas transportation by using the existing natural gas distribution network and infrastructure or pure hydrogen transportation after slightly modifying the existing natural gas distribution network and infrastructure [8–10].

Lynch et al. [11] first proposed adding hydrogen to natural gas, which could greatly increase the operation risk of gas pipelines [12]. In view of this, this paper summarizes and discusses the research status of some key issues, including the influences of hydrogen-blended natural gas transportation on pipelines and components along the pipelines, the safety of hydrogen-blended natural gas pipelines, pipeline integrity management, and relevant standards and specifications. Moreover, this paper also gives some relevant suggestions for the future development of hydrogen-blended natural gas transportation.

2. Influences of hydrogen-blended natural gas transportation on pipelines and components along the pipelines

2.1. Pipe compatibility

In the hydrogen-blended environment, the interaction between hydrogen and pipe results in the degradation of mechanical properties such as hardness, plasticity, and toughness, thus affecting the safety of pipelines [13–16]. Solving the compatibility problem between pipes and hydrogen-blended natural gas is the primary challenge in implementing hydrogen-blended pipeline transportation. It is found that hydrogen-blended natural gas has high compatibility with traditional non-metallic materials. Still, it is easy to cause hydrogen damage to metal components and parts in the natural gas transportation system, threatening pipelines' safe operation. Therefore, the research on pipe compatibility mainly focuses on metal materials. The manifestation patterns of hydrogen damage include hydrogen embrittlement, hydrogen-induced cracking, and hydrogen bubbling, among which hydrogen embrittlement poses the greatest risk [17].

Hydrogen-induced cracking and hydrogen bubbling are two forms of hydrogen damage caused by the combined action of hydrogen atoms and molecules, requiring no external force [18,19]. Hydrogen atoms enter the metal interior and gather into hydrogen molecules at defect sites. With the diffusion of hydrogen atoms, the concentration of hydrogen molecules increases, and the pressure is enhanced. When the pressure exceeds the critical value, some dislocations may be induced in local zones within the metal, causing the failure of the metal. In the steels with high yield strength and no obvious delamination defects, radiated microcracks are easy to be induced; if the yield strength of steels is low or there are obvious delamination defects, hydrogen bubbling is easy to occur, especially at the junctions of inclusions and the matrix.

Hydrogen embrittlement can bring more serious harm than hydrogen-induced cracking and hydrogen bubbling. Due to the small volume and strong activity of hydrogen atoms, it is easy for them to dissolve in the lattice of metal materials and produce massive defects in the metal materials, thus greatly reducing the ductility and tensile strength of the materials, causing hydrogen embrittlement [20–22]. If pipeline cracks exist, crack initiation will be induced with hydrogen enrichment even without external force. Scholars and research institutions have researched hydrogen embrittlement of pipes from microscopic and macroscopic perspectives [23]. At the microscopic level, the molecular dynamics method was used to study the failure mechanism of pipes in a hydrogen-rich environment. An electron microscope was used to observe the microstructure changes of materials. Sanchez [24] studied the diffusion mechanism of hydrogen atoms through iron lattice interstices. They found that hydrogen atoms could weaken the interactions between iron atoms, thus generating many high-energy grain boundaries that make capturing hydrogen atoms easier. Due to lattice defects in the pipes, typical deformation and cracking can occur in a gaseous hydrogen environment [25]. Zhang and Song's [26,27] research showed that hydrogen entering iron lattice interstices could cause lattice distortion, making α-Fe more prone to mismatch nucleation and reducing its yield strength; if the hydrogen atoms were adsorbed on the defect surface for a long time, they would further promote the crack propagation. Wang et al. [28] studied the change laws of the lattice structure of pipes in a high-pressure hydrogen environment, revealing the causes of hydrogen embrittlement and corrosion. The captured hydrogen and flowing hydrogen had different hydrogen embrittlement mechanisms [29–31]. The former induced hydrogen embrittlement by enhancing nucleation and growth of pores around inclusions or sediments in the steel and caused ductile fracture; by contrast, the latter mainly promoted quasi-cleavage fracture along the {101} cleavage plane. The plastic strain played a decisive role in the two hydrogen embrittlement mechanisms [32].

At the macroscopic level, the research mainly focuses on testing the mechanical properties of materials in a hydrogen environment, including tensile properties, fatigue properties, fracture toughness, and crack propagation [33–36]. Through the above tests, the basic mechanical parameters of the materials in a hydrogen environment can be obtained, which provides an important basis for pipeline design and operation. To better understand the influences of the hydrogen environment, the United States and Japan have conducted tests and evaluations on most materials used in the hydrogen environment and established a reference database system for anti-hydrogen embrittlement technology of commonly used materials [37]. The universities and research institutions in China are also actively promoting the establishment of the hydrogen and metal compatibility database of self-made materials. For example, the influences of hydrogen-rich natural gas on the mechanical properties of X80 pipeline steel were deeply explored [38–40]. Moreover, the fatigue life, fracture strength, and material deterioration laws of X80 steel in a blended gas environment with different hydrogen blending ratios of 0, 5 %, 10 %, 20 %, and 50 % under an internal pressure of 12 MPa were summarized. On this basis, the safety and applicability of X80 steel in a hydrogen-blended natural gas environment were evaluated comprehensively and systematically. The fatigue initiation curve of the API X52 pipe drawn by Capelle et al. showed that the fatigue initiation time of the pipe after hydrogen blending was shortened by two-thirds relative to that without hydrogen blending [41,42]. Lee et al. performed an in-situ tensile test on API X65 samples in a hydrogen environment of 20 MPa [43]. The results showed that the tensile strength and elongation ratio decreased by 3.4 % and 4.1 %, respectively. Shang et al. found that compared with pure hydrogen or natural gas, the fracture mode of GB20-grade steel in the gas mixture changed from ductile fatigue fracture to brittle cleavage fracture, with a significantly increased fatigue crack propagation rate [44]. Hydrogen embrittlement not only depends on the pipe itself but is also closely related to the service conditions of the pipe [45]. If there has been fatigue damage or microcracks in pipelines, these defects can become the preferential sites for hydrogen atoms to accumulate, thus increasing the likelihood of hydrogen embrittlement.

In addition to the influences on the properties of pipe base metal, hydrogen also significantly influences the weld seam of pipe section joints. Zhang et al. found through numerical simulation that residual stress was the main reason for hydrogen enrichment and hydrogen embrittlement failure of X80 steel welded joints [46]. Residual stress at the weld seam increased the risk of hydrogen aggregation. Compared with those without considering the residual stress, the concentration of hydrogen aggregation increased by 2.7 times, and the hydrogen embrittlement coefficient increased by more than 75 %. Ren et al. pointed out that when hydrogen was blended into natural gas, the components along the pipeline, such as compressors, valves, and flowmeters, would also face the risk of hydrogen embrittlement [47].

In recent years, much research has been carried out on the hydrogen embrittlement susceptibility and the prevention and control of hydrogen embrittlement of hydrogen and hydrogen-containing coal gas pipelines [48–51]. The results show that the higher the steel grade, the greater the susceptibility to hydrogen embrittlement and the greater the influence on the service life of pipelines [52]. Existing data demonstrate that CO can effectively inhibit the hydrogen embrittlement of pipeline steels, thus effectively prolonging the service life of pipelines [53–55]. Wang [56] studied the weld seam of the X80 pipeline and established the mathematical relation curve of "$[CO]_{min}$ - hydrogen blending ratio" under the critical hydrogen embrittlement indexes by taking the hydrogen embrittlement index of less than 10 % as the critical value of safe operation of pipelines. In addition, relevant research shows that hydrogen embrittlement prevention and control measures such as alloying hydrogen-resistant steels and preparing various hydrogen-blocking layers on the inner wall of pipelines are mostly suitable for new pipelines but are difficult to be applied to existing pipelines. Reducing gas pressure or controlling the hydrogen blending ratio in pipeline gas is usually recommended to ensure transportation safety, but this will inevitably affect the capacity and efficiency of pipeline hydrogen transportation.

2.2. *Hydrogen blending ratio*

The hydrogen content in the gas mixture will affect the safety of pipeline and equipment, accident risks, and gas combustion states to varying degrees. When determining the reasonable hydrogen blending ratio, many factors such as material, transportation conditions, system equipment, and gas quality should be fully considered to ensure that the hydrogen content in natural gas pipelines does not exceed the safety threshold. With the increasing research on the hydrogen blending ratio of natural gas pipelines worldwide, research institutions in many countries are actively carrying out hydrogen blending demonstration projects. Among them are the NaturalHy project of the EU, the DVGW project in Federal Germany, the GRHYD project in France, the Hydeploy project in the UK, and the Sustainable Amerland project in the Netherlands, all achieving remarkable results [57]. In some demonstration projects, the highest hydrogen blending ratio has reached 20 %, which confirms the feasibility of hydrogen blending in natural gas pipelines. Russia has also announced that it will gradually increase the hydrogen blending ratio in the Nord Stream 2 gas pipeline to reduce carbon dioxide emissions, improve air quality, and meet the demand of the European market. Based on the comprehensive analysis of hydrogen blending demonstration projects in Europe, the hydrogen blending ratio is between 2 % and 20 %, and the maximum hydrogen blending amount is 285 m^3/h. However, the application scope of these demonstration projects is limited to local regions and does not realize full-range coverage. The allowable hydrogen blending ratios of natural gas pipelines in various countries are listed in Table 1.

According to the research of Irfan et al., different types of pipe network equipment have different acceptabilities of hydrogen blending ratio [59]. Specifically, the compressor is the key facility of the gas transportation system, and only 10 % hydrogen is allowed to be blended in. The allowable blending ratio of the distribution pipe network and gas storage equipment is 50 %; the hydrogen blending ratio accepted by terminal users is between 20 % and 50 %. Therefore, the key equipment in the system should be comprehensively considered when determining the hydrogen blending ratio. Hafsi et al. established a dynamic model of the change of

Table 1
The allowable hydrogen blending ratios of natural gas pipelines in various countries [58].

Country	The allowable hydrogen blending ratio
Germany	2 % or 10 %
France	6 %
Spain	5 %
Austria	4 %
Switzerland	2 %
Lithuania	2 %
Finland	1 %

the circumferential stress of a node in the pipe network with time by taking the allowable stress of X52 pipe steel as the constraint condition [60]. It was found that when the mass ratio of hydrogen exceeded 2/3, the maximum transient value of circumferential stress exceeded the allowable stress of X52 pipe steel; it could avoid damaging the original gas pipeline by setting the hydrogen mass ratio at 30 %. Tabkhi et al. set the transmission power as 65 % of the pipeline's maximum capacity to evaluate the influences of hydrogen blending on pipeline energy and gas flow rate [61]. Finally, they concluded that the maximum mass ratio of hydrogen blending was 6.6 %. According to the study of Messaoudani et al., when the volume fraction of hydrogen was greater than 10 %, the measurement accuracy of some inspection instruments would be affected due to their low sensitivity to hydrogen, resulting in the failure risk of pipeline system detection instruments [62]. Differently, Daniel et al. [63](Jones et al., 2018). believed that when the hydrogen content was less than 17 %, it would not cause damage to the inspection instruments; however, once the hydrogen content was excessive, the pipeline and terminal facilities needed to be replaced.

China's natural gas pipeline network system has been established, and transportation technology is becoming more and more perfect. By the end of 2021, the total length of China's main natural gas pipelines had reached 11.6×10^4 km [64], providing reliable equipment support for hydrogen transportation and greatly reducing transportation costs. In 2019, the "Chaoyang Renewable Energy Hydrogen Blending Demonstration Project" [65] in China first attempted to blend hydrogen produced from water electrolysis with natural gas, achieving an independent gas supply for a commercial user with a hydrogen blending ratio of 10 %.

2.3. Summary

The degree of hydrogen damage is affected by many factors, including hydrogen partial pressure, oxygen content, material properties and microstructure, strain rate, and ambient temperature. Therefore, special attention should be paid to selecting pipe materials when choosing hydrogen transportation pipelines. For built-up pipelines, the damage inspection and repair should be paid much attention to, and the hydrogen blending ratio and transportation pressure should be controlled. Currently, there is no unified definition for hydrogen blending ratio (mass fraction or volume fraction), leading to inconsistent research conclusions. Moreover, current research mainly focuses on qualitatively describing the influencing factors under experimental conditions but pays little attention to the mode, mechanism, influence degree, and preventive measures of hydrogen damage. In addition, the quantitative relationship between the hydrogen blending ratio and material damage also needs to be further clarified [66].

3. Study on the safety of hydrogen-blended natural gas pipelines

The flow model of a gas mixture of hydrogen and natural gas significantly differs from the traditional transportation model of purely natural gas regarding accident characteristics and evolution laws. The characteristics of low ignition point, wide explosion area coverage, and large diffusion coefficient of hydrogen determine that special attention must be paid to the occurrence of safety accidents, such as leakage accumulation, combustion, and explosion, in the transportation process of the gas mixture. With the increase of hydrogen content, the occurrence probability of these accidents will also change. Previous studies show that the flame propagation speed and the flame temperature of hydrogen-blended gas are higher than those of conventional natural gas, which may lead to more intense combustion or explosion, thus greatly affecting the determination of safety distance. Therefore, it is particularly important to study the safety accidents such as leakage accumulation, combustion, and the explosion of hydrogen-blended gas pipelines.

3.1. Properties of natural gas and hydrogen

The main ingredient of natural gas is methane. The physical and chemical properties of hydrogen are significantly different from those of methane. Table 2 provides the values of relevant properties of methane and hydrogen.

Compared with hydrogen, methane has higher density, viscosity, volumetric calorific value, and solubility in water. In contrast, hydrogen has higher heat capacity, diffusivity, mass calorific value, flame temperature, spontaneous combustion temperature, and greater explosion and fire hazard. Due to differences in physical and chemical properties, blending hydrogen into the natural gas pipeline network will change the original natural gas's combustion and thermal properties and even cause the decompression station's

Table 2
Property comparison of hydrogen and methane [62].

Property	Hydrogen	Methane	Unit
Molar mass	2.02	16.04	g/mole
Critical temperature	33.2	190.65	K
Critical pressure	13.15	45.4	Bar
Steam density at normal boiling point	1.34	1.82	Kg/m^3
Steam density(T = 293.15 K and P = 1 bar)	0.0838	0.651	Kg/m^3
Specific heat capacity(T = 293.15 K and P = constant)	14.4	2.21	kJ/kg/K
Specific heat ratio (Cp/Cv)	1.4	1.31	–
Mass lower calorific value	120	48	MJ/kg
Volume lower calorific value at 1 atmospheric pressure	11	35	MJ/m^3
Maximum flame temperature	1800	1495	K
Explosion limit	18.2–58.9	5.7–14	Vol % in air

temperature to drop [67]. In addition, Altfeld et al. found that hydrogen blending to the natural gas pipeline network would cause the decline of the main combustion characteristic parameter, i.e., the Wobbe index, thus affecting the safety of hydrogen-blended gas transportation in natural gas pipelines [68].

3.2. Leakage and accumulation of hydrogen-blended natural gas

The permeation rate of hydrogen is generally four to five times faster than that of methane. Under the same conditions, the hydrogen leakage from the pipeline is about 1.3–2.8 times that of methane and four times that of air [69]. The diffusivity of hydrogen in air is greater than that of natural gas. Under the same pressure and leakage size, hydrogen blending with natural gas can form a lighter gas mixture with a higher diffusion coefficient and larger volume flow rate [70]. In the transportation process of hydrogen-blended natural gas, leakage usually leads to gas enrichment, asphyxiation, and even explosion hazard. Therefore, it is necessary to conduct in-depth research on the leakage and accumulation behaviors of the gas mixture to ensure safety.

Some scholars have simulated the diffusion of pipeline leakage after hydrogen blending. Subani et al. compared the simulated and measured leakage locations and found that hydrogen blending would affect the accuracy of inspection results [71]. Wilkening et al. established the small-hole leakage models of the hydrogen-methane mixture and pure methane in the pipeline under windy and no-wind conditions, respectively [72]. The results showed that the leakage rate and leakage amount of the gas mixture were much higher than that of methane. However, due to the low density and high hydrogen buoyancy, hydrogen accumulation near the ground was small, reducing the gas mixture's combustion risk. Liu et al. conducted a simulation study on the leakage and diffusion characteristics of high-pressure hydrogen and natural gas [73]. It was found that, under the same conditions, the initial leakage rate of hydrogen was much higher than that of natural gas; after hydrogen leakage and diffusion, larger and more concentrated clouds would be generated, and it was easier for hydrogen to reach consistency with the surrounding pressure. The hydrogen cloud after leakage was mainly concentrated at a high altitude while the natural gas cloud was near the ground, so the risk of natural gas leakage was greater than that of hydrogen. Chen et al. analyzed and discussed the safety-related characteristics of natural gas after hydrogen blending under typical scenarios [74]. The research showed that the hydrogen blending ratio increased, and the leaked gas mixture's thermal radiation area and potential influence radius decreased. In contrast, the leakage volume flow rate, erosion index, leakage diffusion range, and combustible gas inspection index increased.

In addition, some related institutions and scholars have studied and discussed the relationship between leakage risk and the hydrogen blending ratio of hydrogen-blended natural gas. The results showed that blending hydrogen into the natural gas pipeline network would increase the leakage risk, but the risk could be reduced when the hydrogen blending ratio was less than 20 % [75]. The researchers from the University of Waterloo also found that when the hydrogen blending ratio was lower than 20 %, the leakage and combustion risks caused by hydrogen were limited and did not significantly increase the leakage amount. However, the leakage amount would be doubled when the hydrogen blending ratio was greater than 20 %. The NaturalHy project found that hydrogen-blended gas had similar leakage characteristics to natural gas in buildings, but the concentration and accumulation volume of the hydrogen-blended gas increased with the increase of the hydrogen blending ratio; when the hydrogen blending ratio was less than 50 %, the increased amplitude of the gas concentration and accumulation volume would decrease.

The accumulation behavior of hydrogen-blended natural gas after leakage is restricted by many factors, including leakage rate, leakage locations, and leakage space. Lowesmith et al. tested hydrogen-blended natural gas leakage and accumulation behavior in civil buildings [76]. They concluded that under the same leakage pressure, the blending of hydrogen would increase the leakage rate of gas; when the hydrogen blending ratio was less than 50 %, the gas accumulation concentration was only slightly higher, but when the hydrogen blending ratio was more than 50 %, the gas accumulation concentration would increase significantly; when the hydrogen blending ratio was more than 70 %, the gas accumulation was more severe.

Because the density and molecular volume of hydrogen are smaller than those of methane, its permeation rate is higher than that of natural gas. As a result, hydrogen-blended natural gas pipelines are also prone to leakage during transportation, especially in non-metallic materials (such as PE and PVC) pipelines. In the Netherlands, when the hydrogen blending ratio of a hydrogen-blended natural gas pipeline network reached 17 %, the annual hydrogen leakage amount was only 5×10^{-4}% of the total hydrogen blending amount. This data indicates that although hydrogen's permeation rate and diffusion coefficient are larger than those of natural gas, the influence of leakage can be approximately negligible compared to the total pipeline throughput.

3.3. Combustion and explosion of hydrogen-blended natural gas

Blending hydrogen in natural gas greatly increases the flame speed and temperature, resulting in violent combustion and even explosion [77]. The study on the combustion and explosion characteristics of hydrogen-blended natural gas can provide an important reference for determining the safety distance during the installation of the pipe network system [78]. In addition, the blending of hydrogen will increase the severity of the explosion, which can cause harm to infrastructure, human life safety, and the environment, posing serious safety risks. Therefore, studying the explosion mechanism, hydrogen blending ratio, and explosion characteristics of hydrogen-blended natural gas significantly prevents explosion accidents in hydrogen-blended pipelines. Both hydrogen and methane are inflammable gases that are highly dangerous in fire and explosion. Appropriate safety measures can be taken in real-time only when explosion limits, and conditions are fully mastered. The explosion limit oxygen content (LOC) of hydrogen is different from that of methane because the explosion limit (EL) of hydrogen is wider than that of methane. Despite some differences, the LOC and EL of the hydrogen/methane mixture can be estimated by using the Le Chatelier rule:

$$LOC = \frac{1}{\lambda/\boldsymbol{LOC}_{\mathbf{H_2}} + (1-\lambda)/\boldsymbol{LOC}_{\mathrm{CH_4}}} \quad (1)$$

[78]

$$EL = \frac{H_2}{\lambda/EL_{H_2} + (1\text{-}\lambda)/EL_{CH_4}} \quad (2)$$

[78]where λ is the hydrogen content of fuel; LOC_{H_2} is the content of oxygen limiting hydrogen explosion; LOC_{CH_4} is the content of oxygen limiting methane explosion; EL_{H_2} is the explosion limit of hydrogen; EL_{CH_4} is the explosion limit of methane.

Accumulated combustible gas in confined space is prone to explosion, producing large overpressure. Ma et al. conducted hydrogen-methane explosion simulation experiments to investigate this property in a 5 L container and a 64 m^3 room, respectively [79]. The results showed that the maximum pressure produced by the explosion decreased slightly with hydrogen blending and that the pressure rise rate and flame speed increased with the increase of the hydrogen blending ratio. In addition, deflagration occurred in a partially confined space with an open vent. Ma et al. then conducted numerical simulations to study the explosion behavior of hydrogen-blended natural gas at different hydrogen blending ratios in partially confined space by numerical simulation. Compared with the completely confined space, the deflagration pressure was significantly reduced in a partially confined space. The pressure boost rate was also greatly slowed, but the flame speed increased. With the blending of hydrogen, the maximum pressure, pressure boost rate, and combustion rate are all higher than those of natural gas. In addition, ventilation widens the danger zone, induces secondary combustion or injury, and reduces the risk of shock waves. Wilkening et al. took the explosion accident of a high-pressure natural gas pipeline in Belgium as the research background and compared the gas cloud distribution and explosion consequences after leakage of a high-pressure hydrogen pipeline and natural gas pipeline under different wind speed conditions [72]. The results showed that the hydrogen cloud was further away from the ground or buildings due to its low density, thus reducing the likelihood of combustion.

The explosion test of a hydrogen-methane mixture in an open space showed that the influence of the hydrogen blending ratio below 25 % on the maximum overpressure was small, even lower than the overpressure produced by pure methane [80]. Thus, it was concluded that blending less than 25 % hydrogen into the natural gas network did not increase the explosion risk. After hydrogen blending, the flame propagation speed increased sharply, and the blended gas burnt violently in open space, which might lead to an explosion. However, the explosion laws differed in different space forms (open space, partially confined space, completely confined space) and different hydrogen blending ratios [49]. When the hydrogen blending ratio exceeds 40 %, the risk of explosion changing to detonation increases [81]. When the hydrogen blending ratio was 24 %, the high-pressure jet flame of hydrogen-blended gas appeared similar to that of purely natural gas at a pressure of 6 MPa. However, the flame length of the gas mixture was smaller than that of natural gas, resulting in a higher surface heat load of the hydrogen-blended natural gas pipeline than that of the natural gas pipeline. The pressure of hydrogen-blended natural gas decreased faster, and its overall energy was less, so its risk was lower than that of natural gas under the same operating pressure. In addition, Lowesmith further studied the gas leakage and combustion laws of ultra-high pressure natural gas and hydrogen/natural gas mixture with a hydrogen blending ratio of 22 % after the complete pipeline rupture [82]. Due to the higher density of natural gas than that of the gas mixture, the pressure in the gas pipeline decreased slowly, but the leakage mass was higher. The hydrogen blending did not significantly increase the fire risk after the pipeline rupture, and the combustion heat radiation of the gas mixture was slightly reduced. Shen et al. also showed increased hydrogen content in hydrogen-blended natural gas would significantly increase the explosion risk and harm severity. Still, the harm degree was small when the hydrogen content was lower than 20 % [83].

Some scholars combined experiments and numerical simulation to study the explosion laws and flame characteristics of hydrogen-blended natural gas after leakage. Wang et al. established a jet flame prediction model for hydrogen-blended natural gas, based on which they realized the prediction of flame length, explosion velocity, and radiation capacity [84]. Middha et al. predicted the flame propagation speed and explosion limit of hydrogen-blended natural gas [78]. They simulated the explosion process of the leaked gas mixture under different scenarios (i.e., private garage, public parking lot, and tunnel). When the hydrogen volume fraction was 8 % and 20 %, the laminar combustion rate of the gas mixture was 10 % and 30 % higher than that of pure methane, respectively, indicating that the hydrogen-blended gas mixture had a stronger explosive performance. Based on the worst-case prediction, the explosion intensity of the gas mixture was much stronger than that of pure methane, except for the tunnel scenario. Wang et al. studied the radiation characteristics of the jet flame of pure hydrogen and hydrogen/methane gas mixture [85]. The predicted flame length and radiative heat release fraction agreed with the experimental results, and the surface-emission power of jet flame was almost unaffected by the ground reflectance. After the gas mixture of hydrogen/air, methane/air, or propane/air exploded in a confined space, there was no significant difference in the temperature at different locations. Still, the hydrogen/air mixture had a higher peak explosion pressure. Hua et al. found that the maximum temperature on the flame axis of jet flame caused by the failure of the hydrogen-blended natural gas pipeline was only related to the hydrogen blending ratio [86]. At the same time, its length increased with the increase in pipeline pressure or nozzle size.

3.4. Summary

As seen from the above studies, many investigations have been carried out on the safety of hydrogen-blended natural gas pipelines, but most are not universal. In particular, many scholars have reached inconsistent conclusions regarding the influences of the hydrogen blending ratio on leakage properties and combustion and explosion characteristics, thus bringing certain difficulties to determining the hydrogen blending ratio. In addition, some simulation and experimental studies on the leakage and explosion of hydrogen/methane gas mixture are conducted in buildings or confined spaces. It remains to be verified whether the conclusions apply to hydrogen-blended natural gas pipelines. In the future, it is still necessary to carry out in-depth research on the safety of natural gas pipelines with different hydrogen blending ratios and find out the accident characteristics and evolution laws of leakage, accumulation, combustion, and an explosion of hydrogen-blended natural gas pipelines, providing strong technical support for emergency repair of natural gas pipelines.

4. Pipeline integrity management

Integrity management is indispensable to the safe operation of pipelines. Perfect integrity management can effectively identify and reduce the risks that may occur during pipeline operation. Integrity management generally involves identifying risk factors, defect inspection, failure assessment, defect repair, and prevention and protection. Risk assessment is an important part of integrity management. It requires a comprehensive consideration of existing pipeline information to identify the risk events that can cause pipeline failures and evaluate the possibility of their occurrence and the severity of consequences. However, due to the numerous influencing factors, the possibility and severity of consequences vary with the transmission media, pipeline types, operating conditions, and geographical environment. Hence, it is impossible to give unified conclusions.

Using quantitative risk assessment, the Gas Technology Institute (GTI) of the United States studied the influences of corrosion, material defects, and external damage on the hydrogen-blended transportation system. It quantified them into different grades of 0–50. Moreover, it was concluded that the influence of hydrogen blending on pipeline risk was small when the hydrogen blending ratio was less than 50 % [82]. Chen et al. [87] and Messaoudani et al. [62] conducted a quantitative risk assessment on hydrogen-blended gas pipelines. They pointed out that the probability of combustion after leakage was the key factor affecting the assessment results. When the hydrogen blending ratio was high, the probability of spontaneous combustion increased. The blending of hydrogen could lead to the reduction of ignition energy, the acceleration of leakage, and the expansion of the combustible range of the gas mixture. The increase in the hydrogen blending ratio would increase leakage and explosion risks.

Existing integrity management standards are all formulated for natural gas pipelines. However, the blending of hydrogen changes the pipelines' operating environment, degrading the material properties and affecting the failure mode of the pipelines. Hence, the standards for integrity management should also be changed accordingly. Based on the experience from demonstration projects, the NaturalHy project has developed software to assess the failure probability of hydrogen-blended natural gas pipelines under different integrity management scenarios [61]. The assessment items included the critical crack size, inspection techniques, and repair methods [40]. It was found that hydrogen blending could significantly affect the allowable initial crack size and that the influence degree depended on the factors such as hydrogen blending ratio and internal pipeline pressure [74]. Naturally, these conclusions still needed to be confirmed by the pipeline basic data and compatibility data of pipe materials. This project also explored the defect detection capability of existing inspection tools in hydrogen-blended natural gas pipelines. The defects of hydrogen-blended natural gas pipelines could be detected effectively by improving the inspection tools. The time interval for defect inspection was determined by careful consideration of hydrogen blending ratio, load, pipeline geometry, and calculation results of pipeline defect and failure probability based on in-line inspection. Blending hydrogen, especially high-concentration hydrogen, would shorten the inspection period. In addition, the NaturalHy project also researched the three commonly used defect repair methods (composite fiber reinforcement repair, metal casing, and overlaying). The results showed that these methods were equally suitable for the repair of hydrogen-blended pipelines. Improving the existing measures could be applied to the integrity management of hydrogen-blended natural gas pipelines. These results provide strong support for pipeline transportation of hydrogen-blended natural gas. So far, there have been no relevant results on the influences of the hydrogen blending ratio on defect detection and repair effects. Further research is still required to obtain more accurate results.

5. Standards and specifications

Although there is no specific technical standard for hydrogen-blended natural gas transportation pipelines in the international market, several countries have issued relevant standards for pure hydrogen transportation pipelines. Among them, *Hydrogen Piping and Pipelines* (ASME B31.12–2019) drafted by the American Society of Mechanical Engineers, *Hydrogen Pipeline Systems* (CGAG-5.6-2005, revised in 2013) drafted by European Compressed Gas Association, and *Hydrogen Transportation Pipelines* (AIGA 033/06–2006) drafted by Asian Industrial Gas Association provide an important reference for the development of hydrogen transportation pipelines. The ASME B31.12–2019 standard covers many aspects of design, construction, operation, and maintenance, and its contents include four sections of general requirements, industrial piping, pipelines, and Appendices. The standard applies to long-distance piping, sub-piping, and service piping for transporting hydrogen, hydrogen mixtures, and liquid hydrogen from the manufacturing plant to the place of use. Still, it does not apply to piping systems with a hydrogen volume fraction of less than 10 %. The standards of AIGA 033/06–2006 and CGAG-5.6-2005 are suitable for the delivery and distribution system of hydrogen and hydrogen mixture. Still, the molar fraction of hydrogen must be higher than 10 %, or lower than 10 % with the CO content higher than 200 μL/L. There is no specific technical standard for hydrogen-blended natural gas pipelines in China. The related standards include *Storage and Transportation Systems for Gaseous Hydrogen – Part 2: Test methods for evaluating metallic material compatibility in hydrogen atmosphere* (GB/T 34542.2-2018), *Technical Safety Regulation for Gaseous Hydrogen Use* (GB 4962-2008), *Essential Requirements for the Safety of Hydrogen Systems* (GB/T 29729-2022), *Storage and Transportation Systems for Gaseous Hydrogen – Part 1: General requirements* (GB/T 34542.1-2017), *Storage and Transportation Systems for Gaseous Hydrogen – Part 3: Test Method for Determination of the Susceptibility of Metal Materials to Hydrogen Gas Embrittlement* (GB/T 34542.3-2017), and *Design Code for Hydrogen Station* (GB 50177-2019). Among them, the standard of GB/T 34542.2-2018 provides in-situ test methods for the mechanical properties of materials in a hydrogen-containing gas mixture environment, which have certain reference significance for the formulation of relevant standards and specifications for hydrogen-blended natural gas pipelines.

6. Conclusions and suggestions

Hydrogen energy is an important energy carrier for China to achieve the strategic goal of "carbon neutrality". It effectively transports hydrogen on a large scale by blending it into existing natural gas pipelines. The safety of hydrogen-blended transportation is the research focus all over the world. In this paper, a massive literature survey and review were conducted on some key issues, such as the influences of hydrogen-blended natural gas on the pipeline and the components along them, pipeline safety, integrity management, and relevant standards and specifications, and the current status and existing problems of hydrogen-blended natural gas transportation were analyzed and discussed. In describing hydrogen blending ratio parameters, some scholars used mass fraction while some used volume fraction, which should be defined uniformly. The hydrogen blending ratio affects not only the hydrogen damage degree of the pipe but also the leakage and diffusion characteristics and the explosion laws of the gas mixture. Based on existing research results, some recommendations are given as follows:

(1) The characteristics and evolution laws of gas leakage, accumulation, combustion, and the explosion of pipelines and key equipment under different hydrogen blending ratios should be further explored by combining the physical and chemical properties of hydrogen and natural gas and specific prevention and emergency measures must be formulated. According to different scenarios, gas leakage detection equipment should be optimized and designed to improve the susceptibility of leakage gas detection.
(2) The hydrogen damage mechanism of hydrogen-blended natural gas on typical pipes should be further explored by combining theoretical analysis, experimental research, and numerical simulation. Especially the service capacity of high steel-grade pipes in the hydrogen blending environment should be accurately evaluated to determine a reasonable hydrogen blending ratio.
(3) By referring to the existing natural management schemes for gas pipeline integrity, the quantitative risk assessment and safety evaluation methods of hydrogen-blended natural gas pipelines should be explored, and integrity management schemes suitable for pipeline transportation of hydrogen-blended natural gas should be implemented. Moreover, the construction of demonstration projects of hydrogen-blended natural gas pipelines should be strengthened. The standards and specifications for the safe operation of hydrogen-blended natural gas pipelines should be formulated to provide technical references for realizing large-scale hydrogen transportation.

Data availability statement

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

CRediT authorship contribution statement

Xiao Tian: Writing – original draft, Investigation, Funding acquisition, Conceptualization. **Jingjing Pei:** Writing – review & editing, Funding acquisition.

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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