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Review

Hydrogen-Doped Natural Gas and its Transportation Technology

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Abstract: With the continuous increase in energy consumption and the exacerbation of environmental problems, the energy transition is becoming increasingly urgent. Hydrogen, as a clean and zero-carbon energy source, has received extensive attention. Hydrogen-doped natural gas transportation technology has emerged as a promising solution to the challenge of large-scale hydrogen transportation. This article comprehensively reviews the development history of hydrogen doping technology in both China and around the world, and systematically analyzes the effects of hydrogen-doped natural gas on pipeline tubing, including the phenomena of hydrogen embrittlement, hydrogen permeation, leakage diffusion, and ignition explosion. The advantages of this technology, such as significant carbon emission reduction and enhanced energy utilization efficiency, are thoroughly examined. The challenges it faces, such as the elevated safety risks due to the flammability and explosiveness of hydrogen, the immaturity of production technologies, and the inadequacies in regulations and standards, are also meticulously pointed out. Looking ahead, in-depth technical research and development, the innovation of hydrogen production technologies, and the establishment of robust regulations and standards are crucial to facilitating the hydrogen-doped natural gas transportation technology to play a more prominent role in the energy field and to promoting the sustainable development of energy. Additionally, with the continuous innovation and breakthroughs in technology, it is expected that the hydrogen blending ratio can be further increased. For example, the hydrogen blending ratio in some regions may be raised to approximately 30% by 2030, thereby further reducing carbon emissions and accelerating the transformation of the energy structure towards clean and low-carbon.

Keywords: hydrogen-doped natural gas; pipeline transportation; hydrogen embrittlement; hydrogen osmosis

1. Introduction

As global energy consumption continues to climb, the finiteness of traditional fossil energy sources is becoming more and more apparent, while environmental issues are becoming increasingly serious and prominent. In such a situation, energy transition has become an urgent task that is not allowed to be delayed [1]. The search for clean, efficient and sustainable energy alternatives has become a key trend in global energy development. Climate change triggered by greenhouse gas emissions poses an extremely serious threat to ecosystems and human societies [2]. Among many areas, carbon emission reductions in the energy sector are particularly critical and play a key role in an effective response to climate change.

In the background of energy transition and combating climate change, hydrogen energy, as a clean, zero-carbon, environmentally friendly and high energy density energy source, has received widespread attention [3]. However, large-scale transportation of hydrogen is challenging, and hydrogen-doped natural gas transportation technology offers the possibility of solving this problem. Hydrogen-doped natural gas transportation technology makes full use of the existing natural gas infrastructure, which greatly reduces the cost and difficulty of hydrogen application, and significantly reduces the carbon emissions during natural gas combustion. This technology provides a new way for the optimization and upgrading of energy structure, and also provides a new way for green sustainable development.

China has accelerated the development of hydrogen energy industry. On 23 March 2022, the National Development and Reform Commission and the National Energy Administration issued the Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035), which proposes the establishment of a "1 + n" policy system, clarifies the strategic positioning of hydrogen energy, and deploys key tasks for industrial development [4]. In recent years, the research and development of hydrogen-doped natural gas technology has drawn extensive attention. By conducting a literature search on the topics of "Hydrogen-doped natural gas" or "NG blending H_2" in the Web of Science over the past five years, it was found that 59 related papers could be retrieved, and the number of papers has been increasing annually, indicating a booming trend in its research and development. At the same time, a patent search on the same topics in the China National Intellectual Property Administration within the past five years yielded 195 related patents, with the number also constantly on the rise. This demonstrates that both the theoretical research and practical application exploration of hydrogen-doped natural gas technology are in a stage of rapid development, holding broad prospects for the future. However, despite the urgent needs of energy transition and the continuous progress of hydrogen energy application technology, which have led to the research on hydrogen-doped natural gas technology receiving increasingly widespread attention and advancing rapidly, it still faces many challenges. These challenges mainly involve the development of technical standards, cost control in large-scale applications, and public acceptance of its safety.

In the future, with the deepening of research and continuous innovation of technology, hydrogen-doped natural gas technology is expected to play a more important role in the energy field.

2. Development History of Hydrogen-Doped Natural Gas Transportation Technology in China and Worldwide

In foreign countries, the hydrogen-doped natural gas transportation technology is evolving rapidly. Many countries have initiated relevant programs and have achieved certain outcomes. Countries like Spain, the United Kingdom, the United States, Germany, Belgium, Italy, etc. have taken actions. Spain Nortegas started the first pilot project for hydrogen-doped natural gas and the German utility project achieved a hydrogen doping rate of 20% [5]. According to the International Energy Agency, if the ongoing projects are implemented, they will be more than 700 times larger, with a total hydrogen blending capacity of more than 2 million metric tons. However, there are technical and cost challenges with this model, and the ability of pipelines to accommodate hydrogen in varying proportions varies from country to country. Different hydrogen doping ratios have been tested in international projects such as those in the European Union, the Netherlands, France, and the United Kingdom.

In order to assess the effect of hydrogen blending on the existing natural gas pipeline network, 39 European Union partners initiated the NaturalHy project in 2004 [6]. The two strategies of "green hydrogen" and "hydrogen transportation" accelerate the transformation of the hydrogen economy, as shown in Figure 1.

The project focuses on combustion characteristics, pipeline durability, energy capacity of the pipeline, and energy loss due to gas leakage in the study of hydrogen-doped natural gas. Integrated management software was developed to assess the probability of pipeline failure. Experiments and studies related to pipeline fracture toughness and safety risks have been conducted for hydrogen-doped natural gas from 100%, 70%, and 50% to 20%. It was concluded that the pipeline would be able to safely transport 20% of the hydrogen-doped natural gas under the existing conditions without additional measurement and control equipment, with a very low risk of explosion.

On 10 November 2023, the National Pipe Network Group successfully organized the first full-scale hydrogen-doped natural gas pipeline release jet fire test and closed space leakage combustion test. The pipe adopted X65 steel grade, the diameter is 323.9 mm, the height of the release riser is 5 m, the test pressure is 12 MPa, and the maximum hydrogen blending ratio is 30%. This fills the gap in the verification test of hydrogen-doped venting combustion test for long-distance natural gas pipelines in China. Meanwhile, the test laid an important foundation for the self-controllable hydrogen blending transportation technology of long-distance natural gas pipeline. At the same time, in the demonstration platform of Ningdong hydrogen-doped natural gas pipeline in Yinchuan, the proportion of hydrogen in the 397 km long pipeline reached 24% in safe and stable conditions [7]. By the end of 2022, the total mileage of oil and gas pipelines in China had reached 185,000 km. It has been proved that when the hydrogen blending ratio is 20%, it is feasible to transport more than 10 million tons of hydrogen. This was equivalent to over 560 billion kilowatt-hours of green electricity and significantly lowered the cost of hydrogen. In 2024, the first comprehensive experimental platform for hydrogen doping of town gas was put into operation in Shenzhen, marking a new stage in the application of hydrogen energy [8].

China holds the largest installed capacity for renewable energy in the world. By 2030, the installed scale of hydrogen production from renewable energy is anticipated to reach 100 million kilowatts and approach 100 million tons. By 2030, the demand for hydrogen energy in China is projected to reach 37.15 million tons, accounting for approximately 5% of the end-use energy consumption. Hydrogen energy is anticipated to make up 10% of China's end-use energy consumption by 2050 [9].

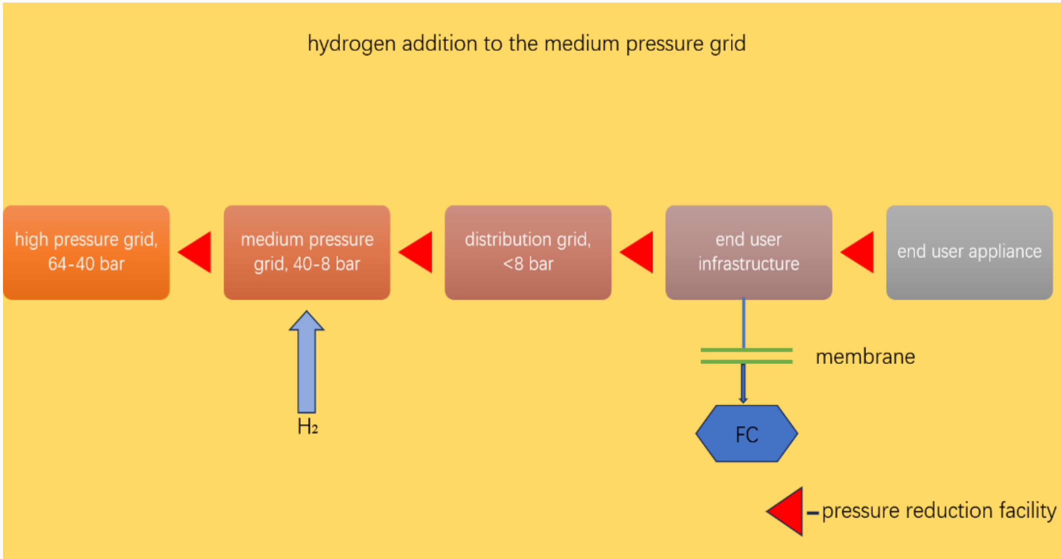

Figure 1. Concept map of NaturalHy (FC, Fuel Cell).

3. Influence of Hydrogen-Doped Natural Gas on Pipeline Tubing

3.1. Hydrogen Embrittlement

Hydrogen embrittlement refers to the interaction of hydrogen into the metal and the metal matrix, resulting in a reduction in the toughness of the piping material, or even a brittle fracture or cracking phenomenon [10]. The occurrence of hydrogen embrittlement is affected by a combination of factors, including the level of transportation pressure, the size of the hydrogen doping ratio, the strength of the pipe itself, and the operating time of the pipe.

Zhou D et al. [11] investigated the effect of natural gas/hydrogen mixtures on the tensile properties of X80 pipeline steels at 12 MPa hydrogen pressure with 1.0, 2.2, and 5.0 vol% of hydrogen by simulating hydrogen mixed natural gas with the help of nitrogen and hydrogen. The results showed that, the hydrogen-doped natural gas had little effect on the tensile and yield strengths of the alloy. The ratio of the fractional shrinkage and elongation at break decreased significantly as the volume ratio of hydrogen increased. The hydrogen embrittlement susceptibility rose. Dong Jingnan et al. [12] evaluated the hydrogen embrittlement susceptibility of L80 steel under different hydrogen pressures at room temperature. The hydrogen embrittlement sensitivity of L80 steel under 3–12 MPa hydrogen pressure was investigated by notch slow strain rate tensile test and fracture morphology analysis. The results show that when the hydrogen pressure is lower than 5 MPa, L80 steel has no obvious brittleness at room temperature, and when the hydrogen pressure is higher than 8 MPa, it has obvious brittleness. Under hydrogen pressure of 3 MPa to 12 MPa, the micromorphology at the center of the main section of the tensile specimen of L80 steel changes from a dimple morphology to a coexistence of dimples and cleavage morphology, at the same time, the micromorphology at the edge gradually changes from a dimple morphology to cleavage and the change rate of the section shrinkage increased from 16.19% to 46.79% gradually. With the increase of hydrogen pressure, the plasticity loss of L80 steel increases, the fracture shows obvious embrittlement characteristics, and the hydrogen embrittlement sensitivity increases gradually.

Many scholars have found through research that as the hydrogen pressure increases, the ratio of fracture toughness gradually decreases [13–16]. This implies that the energy required for hydrogen to initiate ductile cracks is significantly reduced. A higher hydrogen partial pressure leads to more hydrogen atoms entering the material, making the material more susceptible to cracking during the loading process.

The mechanism of hydrogen embrittlement is still unclear at present, however, a series of measures are employable to reduce the harm it brings, such as reducing operating pressure or hydrogen blending ratio, leaving sufficient safety margin in new pipeline design, regular detection and timely replacement of key components. In the process of Hydrogen-doped natural gas transportation, it is necessary to strictly control the proportion of hydrogen doping and optimize the treatment process to ensure the safe operation of pipeline facilities. It is worth noting that the possibility of hydrogen embrittlement is increasing with the pipe grade, with X80 and X70 more likely to suffer from hydrogen cracking than X60 [17]. And most researchers believe that high-strength steel is more prone to hydrogen-induced failure than low-strength steel [18–23].

3.2. Hydrogen Osmosis

Hydrogen permeation behavior refers to the entire process of hydrogen permeation through materials under specific conditions and the specific manifestations presented. At present, the mechanism of hydrogen permeation behavior in the operation of hydrogen pipelines and the influence of their environmental conditions have not been clarified, and the mechanism of the permeation behavior on the mechanical properties of pipeline materials has not been determined [24]. Hydrogen permeation behavior is in the spotlight in contemporary critical areas of hydrogen storage and transportation due to its potential to cause hydrogen leakage, which in turn adversely affects the safety and operational efficiency of the system. Hydrogen permeation behavior is influenced by a combination of factors, including the nature of the material itself (e.g., crystal structure, chemical composition, and microstructure), the environmental conditions (e.g., temperature, pressure, and hydrogen concentration), and the state of the material surface (e.g., roughness, oxidation, and coatings), all of which have a significant impact on hydrogen permeation behavior.

Li et al. [25] investigated the stress corrosion cracking behavior of X100 pipeline steel by slow strain rate tensile test, hydrogen permeation test and surface morphology analysis. They discovered that as the cathodic potential declined, the hydrogen penetration current and stress corrosion susceptibility of the specimen rose. The reduction in cathodic potential facilitated the hydrogen precipitation reaction. Yao et al. [26] carried out the hydrogen permeation test to study the diffusion parameters of hydrogen under electrochemical environment and clarified the hydrogen distribution in X65 pipeline steel under different cold deformation degrees by hydrogen micro-printing test. They discovered that the hydrogen permeation current density and effective hydrogen diffusion coefficient declined with the increase of cold deformation, while the degree of hydrogen aggregation on the surface of the sample increased with the increase of cold deformation. The in-depth study of hydrogen permeation behavior is helpful to develop materials with better hydrogen permeation resistance and optimize the design of equipment and systems, promoting the healthy and stable development of the hydrogen energy industry.

3.3. Proliferation of Hydrogen-Doped Natural Gas Pipeline Leaks

In the hydrogen-doped natural gas pipeline system, the mixed gas of hydrogen and natural gas escapes abnormally from the pipeline due to pipeline rupture, interface failure, equipment failure and other reasons, and propagates and diffuses in the surrounding environment. This process involves complex physical and chemical changes, including the flow of gases, mixing with ambient air, and changes in concentration, which can pose potential threats to the surrounding environment, personnel safety, and facilities.

By SPS (Simulation Platform for Pipelines) software simulation, Zhu Jianlu et al. [27] found that the hydrogen doping ratio has a marginal influence on the pressure change of horizontal gas pipelines. Furthermore, in contrast to pure natural gas, a hydrogen doping ratio of 30% shortened the time for pipeline repair after leakage by 93%. Jia Wenlong et al. [28] simulated and analyzed the dispersion of hydrogen-doped natural gas leakage within a typical valve chamber of the West-East Natural Gas Pipeline. They discovered that the direction of the leakage port had a more significant influence on the aggregation of methane and hydrogen at the top of the valve chamber and the downward leakage port was not conducive to the aggregation of methane and hydrogen at the top of the valve chamber. Wang et al. [29] constructed a simulation model of leakage and diffusion of hydrogen-doped natural gas pipelines under the influence of obstacles. It was found that the increase of hydrogen blending ratio expanded the horizontal and vertical diffusion range of hydrogen and reduced the diffusion range of methane.

To ensure the safety of hydrogen-doped natural gas pipelines, it is essential to conduct further long-term experiments for a more accurate assessment of the adaptability of the existing gas infrastructure and the establishment of a standard system. Additionally, it is necessary to accelerate the development of cost-effective and efficient green hydrogen production technology to provide sufficient hydrogen sources for urban gas doping with hydrogen. Furthermore, in-depth verification of the key technologies within the “mixing-transmission-use” chain is indispensable. Corresponding standards and specifications for hydrogen-doped natural gas must be developed. Laws and regulations must be strengthened. Eventually, the collaboration among “government, industry, academia, research and application” institutions must be enhanced to facilitate cooperation throughout the entire industry chain development and establish effective sharing platforms and cooperation mechanisms.

3.4. Hydrogen-Doped Natural Gas Pipeline Flares

The explosion of hydrogen-doped natural gas pipeline refers to the phenomenon that the mixture of hydrogen and natural gas in the pipeline burns rapidly under certain conditions due to leakage. This situation has led to a strong shock wave and caused serious damage to the pipeline and its surroundings, posing a threat to lives and property of people.

Shchelkin [30], Lee et al. [31] and Shepherd et al. [32] studied the characteristics of deflagration to detonation in natural gas-hydrogen mixtures. Urtiew et al. [33] were the foremost to point out the transition from explosion to detonation. Ni Jing et al. [34] carried out experimental tests on three premixed gases with different hydrogen doping ratios in a circular semi-enclosed combustion chamber. They found that hydrogen boosted the propagation rate of detonation and there existed a positive correlation between the hydrogen doping ratio and the propagation rate. Yu Jin et al. [35] analyzed the leakage and diffusion rules of hydrogen-doped natural gas with different wind speeds and different hydrogen doping ratios in the presence of obstacles and discovered that as the hydrogen doping ratio rises, the diffusion radius of the lower limit of methane explosion gradually decreased, while the risk of explosion increases accordingly. Wan Xiaogang et al. [36] added a small amount of methane to hydrogen and found that the presence of hydrocarbons reduces the flammability of hydrogen. Zhang Gengxin et al. [37, 38] employed the Schlieren technique to obtain hydrogen-air premixed spherical flame images under specific conditions. The obtained results, including average precision value, critical flame radius, crack length, and average cell area, along with the applicable cell segmentation model, contribute to hydrogen combustion and explosion modelling development.

In the future, with the deepening of relevant research and the development of technology, the safety standard system of hydrogen-doped natural gas pipelines will be further improved to ensure their safe operation. At the same time, China is accelerating the layout of the hydrogen energy industry. It is continuously achieving breakthroughs in hydrogen energy preparation, storage and transportation, as well as infrastructure construction. A number of centralized enterprises have laid out the whole industrial chain of hydrogen production, storage, hydrogen refueling and hydrogen use.

4. The Advantages and Challenges of Hydrogen-Doped Natural Gas Transportation Technology

4.1. The Advantages of Hydrogen-Doped Natural Gas Transportation Technology

The use of hydrogen-doped natural gas in transportation technology significantly reduces carbon emissions in energy consumption. During combustion, hydrogen produces far less carbon dioxide than conventional fossil fuels, which is of great positive significance for mitigating global climate change and achieving the goal of carbon neutrality. By reasonably allocating the ratio of natural gas to hydrogen, it helps accelerate technological innovation and industrial upgrading in hydrogen production, storage, transportation, and other aspects, promoting the development of hydrogen energy from production to application.

Hydrogen-doped natural gas transportation technology has numerous prominent advantages. Regarding energy transition, hydrogen is blended into natural gas as a clean energy carrier, which helps reduce dependence on traditional fossil fuels and promote the transformation of energy structure to low carbon and clean direction. From the perspective of environmental benefits, the product of hydrogen combustion is mainly water. This substantially lowers the emission of pollutants like carbon dioxide, nitrogen oxides, and particulate matter. It is highly significant for the alleviation of climate change and the improvement of air quality. In terms of energy storage and transportation, the infrastructure of natural gas pipelines is already relatively well-developed. The utilization of existing natural gas pipelines for hydrogen doping and transportation reduced the high cost of building new specialized hydrogen transportation pipelines significantly. It enhanced the efficiency of infrastructure utilization and expedited the large-scale promotion and application of hydrogen [39]. Studies have shown that the cost of hydrogen blending in natural gas pipelines is lower than the cost of electricity transmission over distances of more than 1000 km [40]. In addition, hydrogen-doped natural gas improves the combustion characteristics. Hydrogen burns quickly, and improves the combustion speed and combustion efficiency of the mixture. From an economic perspective, the hydrogen-doped natural gas transportation technology facilitates the development of the hydrogen energy industry. It has stimulated investment and employment in related technology research and development and equipment manufacturing, generating new economic growth points.

4.2. The Challenges of Hydrogen-Doped Natural Gas Transportation Technology

Hydrogen is highly flammable and explosive, with a rapid rate of diffusion and a wide range of combustion. A leak in a hydrogen-doped natural gas pipeline during transportation usually results in a build-up of gas, leading to asphyxiation and possibly even an explosion hazard. At present, hydrogen production technology is still immature and it mainly relies on fossil energy reforming, water electrolysis and other methods. There are problems of low efficiency, high energy consumption and high production costs. This makes hydrogen-doped natural gas in large-scale applications seriously constrained. It is necessary to research and develop more efficient and low-cost hydrogen production technology to enhance its economic viability.

Furthermore, the hydrogen-doped natural gas transportation technology is encountering severe challenges in terms of material compatibility. Due to the special nature of hydrogen, the existing natural gas pipeline materials do not fully adapt to the working conditions after hydrogen blending. For instance, Hydrogen gas may cause problems such as embrittlement of pipeline materials and hydrogen permeation, thereby shortening the service life of pipelines, increasing maintenance costs, and potential safety risks. Moreover, in the detection and monitoring links, there is currently a shortage of precise and effective technical means to monitor the hydrogen content in natural gas and the operating conditions of the pipeline in real-time. When confronted with hydrogen-doped natural gas, the accuracy and reliability of traditional detection equipment and methods are greatly reduced and it is difficult to meet actual needs. This brings hidden dangers to the safe operation of the pipeline and makes it difficult to make accurate judgments and handle problems promptly when they occur.

At present, the relevant regulations and standards for hydrogen-doped natural gas and transportation are not yet perfect. There is a lack of clear, unified norms and guidance in the promotion and practical application of the technology, leading to a lack of standardization and consistency in the development of the industry. Therefore, there is an urgent need to develop a comprehensive system of regulations and standards covering technical requirements, safety standards, quality control and other aspects.

5. The Combustion Application of Hydrogen-Doped Natural Gas in Stoves

With the optimization of the energy structure and the unremitting pursuit of clean energy, the hydrogen-doped natural gas transportation technology has become the focus. Stoves, as common gas equipment, have significant combustion performance. Hydrogen has characteristics such as high combustion speed, wide combustion limit and low ignition energy, while the main component of natural gas, methane, burns relatively stably. The combustion characteristics after the mixture of the two depend on the hydrogen blending ratio. Hydrogen blending accelerates the flame propagation speed. An appropriate hydrogen blending ratio optimizes the combustion reaction, improves the thermal efficiency of the stove and reduces incomplete combustion products and energy loss. A low hydrogen blending ratio generally has little impact on the flame stability. When the ratio is high, it is necessary to be vigilant against flashback and flameout. In addition, hydrogen-doped natural gas combustion reduces the emissions of nitrogen oxides, carbon dioxide and other pollutants, and increases the emissions of a small amount of nitrogen-hydrogen compounds [41]. Ma Xiangyang et al. [42] found that when the requirements of natural gas combustion potential and Wopo index were met, the maximum hydrogen mixing ratio in methane reaches 23%. Luo Zixuan et al. [43] found in combustion experiments that when the hydrogen mixing ratio of natural gas was 5%, 10%, 15%, and 20%, the flame stability and the content of carbon monoxide and nitrogen oxides produced during combustion met national standards. In addition, as the hydrogen mixing ratio increases, the content of carbon monoxide in the flue gas decreases, and the thermal efficiency of the furnace improves.

In view of this, the stove needs to be improved. On the one hand, it is necessary to adjust the structure of the burner, such as optimizing the gas nozzle and air channel to ensure uniform mixing and sufficient combustion. On the other hand, the control system needs to be improved to accurately regulate the flow of gas and air, monitor the combustion status in real time, and automatically adjust parameters. In practical applications, there are successful examples in both home and commercial kitchens. However, there are still many challenges, such as inadequate infrastructure for hydrogen supply and storage, compatibility and standardization issues with stoves, and limited public acceptance of new technologies. To solve these problems, a series of measures need to be taken, such as increasing investment in infrastructure construction, establishing unified standards, and strengthening publicity and education.

6. Conclusions

Hydrogen-doped natural gas and transportation technology is of key significance in the energy field. It is being explored both in China and worldwide, with foreign countries making fast progress but facing technical and cost challenges. Technically, natural gas mixed with hydrogen has hydrogen embrittlement and hydrogen permeation effects on pipeline pipes, which may cause hydrogen leakage and affect safety and efficiency. The advantages of this technology are obvious. It reduces carbon emissions, which opens the way for the application of hydrogen and promotes the development of the industrial chain. However, it also faces serious challenges, for example, the low efficiency of hydrogen, the flammability and explosiveness of hydrogen increases the safety risk and the production technology relies on the traditional method. The relevant regulations and standards are imperfect, affecting the standardization of the industry.

Under the premise of no hydrogen resistance modification, it is considered that the average long-distance natural gas pipelines in China can withstand HCNG (Hydrogen enriched compressed natural gas) with a hydrogen blending ratio below 10–20% [44–46]. Assuming that the long-distance natural gas pipelines operate at the designed gas transmission capacity, approximately 14.98–29.96% of China's hydrogen energy consumption demand in 2030 can be transported over long distances in the form of HCNG [47].

The development of predictive models and protection strategies for hydrogen embrittlement and hydrogen permeation, the optimization of hydrogen blending ratio, and the development of low-cost hydrogen production technologies may accelerate the industrial application of this technology. In terms of standards and norms, relevant departments and organizations establish and improve a sound system of regulations and standards. In the future, with technological progress, cost reduction and policy support, hydrogen-doped natural gas transportation technology builds a clean, low-carbon and efficient energy system, which is expected to become a strong support for sustainable development in global energy transformation and promote the future of green energy.

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