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Current Status and Analysis of Natural Gas Pipeline Hydrogen Blending and Transportation Development

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ABSTRACT

Hydrogen doping in natural gas pipelines is one of the means to realize large-scale, long-distance and low-cost hydrogen transportation, but hydrogen doping in natural gas pipelines has brought about non-negligible impacts on pipeline operating conditions, safety and maintenance, etc., and has certain potential safety hazards. To this end, the technical research and engineering application of hydrogen doping in natural gas pipelines at home and abroad are discussed, and the main factors affecting the safe transportation of hydrogen doping in natural gas pipelines are discussed, i.e., physical changes of natural gas caused by hydrogen doping, hydrogen failure, and uneven mixing. The results show that the hydrogen doping of natural gas puts new requirements on the existing pipe materials, and relevant experiments need to be carried out in order to reveal the mechanism of hydrogen failure, and whether gas aggregation occurs after the shutdown of hydrogen-doped natural gas pipelines is closely related to whether hydrogen failure occurs in the pipelines or not. The above results clarify the risks of hydrogen-doped transportation, which can provide a reference for the promotion of large-scale hydrogen-doped mixing and transmission projects and practical operation.

KEYWORDS

Hydrogen-Doped Natural Gas; Hydrogen Failure; Pipeline Transportation.

1. PREAMBLE

As a kind of secondary clean energy, hydrogen energy has the advantages of green environmental protection, high calorific value of combustion, wide range of sources, diverse applications, etc. It is one of the important supports for the global energy transition, and at present, hydrogen energy has become a strategic choice for many countries to seek the development of energy transition[1]. Vigorously develop hydrogen energy is also one of the important strategic objectives to promote China's energy transformation and upgrading and green sustainable development, has been included in the “14th Five-Year Plan” development plan of the key tasks, but also to help achieve the dual-carbon purpose of the important guarantee. 2022 March, the National Energy Administration and the National Development and Reform Commission jointly issued the “Long-term Plan for the Development of the Hydrogen Industry (2021)”, which is the first long-term plan for the development of the hydrogen industry in China. Medium and Long-term Plan for the Development of Hydrogen Energy Industry (2021-2035)”, the plan clearly states that hydrogen energy is an important component of the future national energy development system, and is an important carrier for the realization of environmentally friendly and low-carbon transformation of the energy end-use terminals, and that the hydrogen energy industry is a strategic emerging industry and a key direction for future development. China's renewable resources utilization scale ranks first in the world, relying on geothermal, wind, solar and other renewable resources to prepare green hydrogen has obvious advantages, in 2022 China's hydrogen production of 3.3×10^8t, hydrogen production is located in the world's first, at present, China's annual production of hydrogen has reached 4.1 × 10^8t. However, China's hydrogen industry is mainly distributed in the central and western regions, but the main use of the region is concentrated in the However, China's hydrogen energy industry is mainly distributed in the central and western regions, but the main use areas are concentrated in the southeast coastal areas, the supply and demand regions are imbalanced, and there is an urgent need to develop a matching hydrogen energy storage and transportation deployment system[2], the cost of hydrogen storage and transportation accounts for about 30%~40% of the entire hydrogen energy industry, and the main transportation methods used at present include: long tube trailers, pipeline transportation, low-temperature liquid hydrogen tanker trucks, and solid metal hydride transportation, etc[3], and at present, China mainly utilizes the long tube trailer to transport hydrogen, but there is limited capacity At present, China mainly uses long pipe trailers to transport hydrogen, but there are disadvantages such as limited capacity, high transportation cost, limited transportation distance, etc. Therefore, the cross-regional hydrogen storage and transportation technology that is safe, reliable, efficient, and has a large transportation volume is especially important, and the pipeline hydrogen transportation is more efficient and environmentally friendly than the other transportation modes, and the transportation cost is lower, so the pipeline transportation is the optimal way for large-scale, long-distance, and safe and stable transportation of hydrogen. There are two main ways of pipeline hydrogen transportation: (1) using the existing natural gas pipeline network for hydrogen-doped transportation; (2) new construction or using the existing natural gas pipeline network transformation for pure hydrogen transportation. However, due to the special nature of hydrogen, long-distance pipelines face the challenges of "hydrogen brittleness" and "hydrogen permeability", and pipeline transportation of hydrogen has stringent requirements for pipeline materials, resulting in the construction of hydrogen transportation network infrastructure that requires huge capital investment and a long construction period, which is not yet popularized in large scale in the early stage. In the early stage when hydrogen energy is not massively promoted, laying dedicated pipelines for hydrogen transportation will increase the cost of hydrogen usage. By the end of 2022, the total mileage of built natural gas pipelines in China will be about 12×10^4km. Utilizing the existing well-developed natural gas pipeline infrastructure, blending hydrogen into natural gas for transportation and separating and purifying it at the terminals can significantly reduce the cost investment, and it is the best solution for realizing the large-scale, long-distance, and low-cost transportation of hydrogen energy[4].

2. THE CURRENT SITUATION OF NATURAL GAS PIPELINE HYDROGEN DOPING TRANSPORTATION AT HOME AND ABROAD

2.1. The Current Situation of Natural Gas Pipeline Hydrogen-doped Transportation Abroad

In recent years, many places in Europe and the United States have carried out the application demonstration of natural gas hydrogen-doped transportation, and are trying to carry out large-scale promotion. Natural gas pipeline hydrogen-doped transportation of hydrogen-doped ratio is affected by a variety of factors, resulting in differences in the maximum permissible hydrogen-doped ratio of each country, for example, the European countries Finland, Switzerland, Austria, Spain and France allow the maximum hydrogen-doped ratio of 1%, 2%, 4%, 5% and 6%, respectively, and at present, the maximum permissible hydrogen-doped ratio of natural gas in Germany is 2%, but under certain circumstances can reach 10%. A report from the Australian Renewable Energy Agency (AREA) shows that at hydrogen blending ratios of less than 10%, hydrogen blended natural gas has little impact on natural gas pipelines, equipment, etc[5]. The WindGas Falkenhagen and WindGas Hamburg projects in Germany completed the transportation of natural gas pipelines with a hydrogen doping ratio of 2%[6]. The Ameland project in the Netherlands completed gas transportation with a 20% hydrogen doping ratio[7].

Table 1. Hydrogen blending ratio regulations for natural gas in selected countries

Country	Hydrogen Doping Ratio
Finland	1%
Switzerland, Germany	2%
Austria, Australia	4%
Spain	5%
France	6%

2.2. Current Situation of Hydrogen Doping Transportation in Foreign Natural Gas Pipelines

China's hydrogen pipeline construction started late, but in recent years China's natural gas pipeline hydrogen doping transportation related technology is booming. According to statistics, China has about 17 pipelines have been built or included in the planning, the key hydrogen doping transportation pipeline or project name and related parameters are shown in Table 2[8]. China has made new breakthroughs in the use of existing natural gas pipeline hydrogen doping to achieve long-distance mixing and transmission technology, has designed and completed the Chaoyang Renewable Energy Hydrogen Doping Demonstration Project (hydrogen doping ratio of 10%), Ningxia Yinchuan Ningdong Natural Gas Hydrogen Doping Pipeline Demonstration Project (hydrogen doping ratio of 24%), etc., which provides technical support for long-distance, large-scale hydrogen transportation. In addition, with the rapid development of seawater hydrogen production, the construction of China's first submarine hydrogen doping pipeline has begun in Guangdong Province, with a total length of 55 km and an expected hydrogen delivery capacity of 40×10^8 m^3/a.

Table 2. Key hydrogen doping pipeline projects in China and related parameters

Pipeline project	**length/km**	**Hydrogen transported**
Yangzi-Yizheng Hydrogen Pipeline	40.04	4.0×10^4t
Shaanxi-Nanjing Line Project	97	15.9×10^4t
Jiyuan-Luoyang Hydrogen Pipeline	25	10.04×10^4t
Zhangjiakou Hydrogen Doping Pipeline Demonstration Project	400	$440\times10^4m^3$
Ningxia Ningdong Natural Gas Hydrogen Doping and Carbon Reduction Demonstration Project	7.4	$200\times10^4m^3$
Guangdong Submarine Hydrogen Doping Pipeline	55	$40\times10^8m^3$
Chaoyang Natural Gas Hydrogen Doping Demonstration Project	-	-
Zalutqi-Wulanhot Hydrogen-blended Natural Gas Long-distance Pipeline Project	230	-

3. ANALYSIS OF FACTORS AFFECTING HYDROGEN BLENDING IN NATURAL GAS PIPELINE NETWORK

3.1. Hydrogen - Methane Properties

Natural gas is mainly composed of methane, so the nature of hydrogen-methane mixture of various types of hydrogen-doped natural gas pipeline is an important safety impact factors, as shown in Table 3.

Table 3. Comparison of physical property parameters of hydrogen and methane

	Properties	Hydrogen	Methane
Physical Properties	Molar mass/($kg\cdot kmol^{-1}$)	2.0159	16.0430
	Density at standard conditions/($kg\cdot m^{-3}$)	0.0838	0.6510
Fuel Quality Indicators	Low calorific value/($MJ\cdot m^{-3}$)	10.23	34.04
	High calorific value/($MJ\cdot m^{-3}$)	12.09	37.77
Fuel Safety Indicators	Critical temperature/K	33.20	190.65
	Autoignition temperature/K	793	935
	Explosion limit	4.0%~75.0%	5.3%~15.0%
	Flame propagation speed/($m\cdot s^{-1}$)	2.1	0.4
	Constant pressure adiabatic flame temperature/K	2318	2190
	Diffusion coefficient/($m^2\cdot s^{-1}$)	6.1×10^{-5}	1.6×10^{-5}

When the properties of hydrogen and methane are quite different, when hydrogen is blended into natural gas in different ratios, the properties of hydrogen doped natural gas will also change, and therefore the operating parameters of hydrogen doped natural gas will be different.HAFSI et al[9] focused on analyzing the flow pattern of hydrogen doped natural gas in the annular pipeline network, and found that increasing the ratio of hydrogen doped reduces pressure fluctuations in the pipeline and the power of the gas delivery. The density of methane-hydrogen mixtures is lower than that of pure methane, and one of the effects that the density difference can have is an increase in the volumetric flow rate of gas leakage, with methane-hydrogen pipelines showing greater leakage flow rates compared to methane pipelines with the same leakage size[10].

3.2. Hydrogen Failure

Hydrogen cracking and hydrogen bubbling are the manifestation of hydrogen failure, the process of hydrogen cracking can be divided into six stages[11]: (1) the generation of hydrogen atoms, hydrogen-doped natural gas pipeline in addition to hydrogen inside the pipeline will produce hydrogen atoms, welding, corrosion and other processes will also produce hydrogen atoms; (2) the surface of the steel pipe adsorption generated by the hydrogen atoms; (3) the absorption of hydrogen atoms, due to the hydrogen atoms than the volume of the metal atom Volume is small, easy to be adsorbed by the metal crystal dot matrix gap and aggregation; (4) hydrogen atoms in the internal free diffusion of steel; (5) hydrogen atoms in the diffusion of local aggregation, resulting in crack nucleation, followed by cracks in the tip of the role of the stress occurs rapidly expanding; (6) when the concentration of hydrogen atoms inside the hydrogen trap reaches the threshold value, hydrogen cracking occurs. In addition to hydrogen atoms, hydrogen molecules will be formed inside the hydrogen trap, so that the local pressure inside the steel is too high, and hydrogen bulging bubbles are generated on the steel surface, which ultimately leads to hydrogen failure.

Many scholars at home and abroad for hydrogen doped natural gas pipeline hydrogen failure research. Zhang Han et al[12] that hydrogen will be gathered in the pipeline internal surface, dissociation of the formation of hydrogen atoms, hydrogen atoms will be diffused into the interstices of the molecular structure of the pipe, when the interstices in the hydrogen atoms aggregated to a certain number of interstitial pressure in the interstices increased dramatically, resulting in the expansion of the interstices into the cavity, so that the pipe performance deterioration, hydrogen failure occurs. Haeseldonckx D et al[13] that hydrogen embrittlement is also closely related to the service environment of the pipeline, if the pipeline service time is long, or has been affected by fatigue loss, fatigue cracks, etc., there will be a large number of hydrogen atoms inside the pipeline space, increasing the possibility of hydrogen failure. MENG et al[14] also carried out experiments on the effect of different hydrogen-doped natural gas ratios on the mechanical properties of X80 pipeline steel, and found that with the increase of the hydrogen-doped ratio, the rate of fatigue crack expansion of X80 pipeline steel accelerated significantly, and the susceptibility to hydrogen failure increased. Xing Xiao et al[15] suggested that the temperature affects the intensity of hydrogen embrittlement, and with increasing temperature, the activity of hydrogen atoms in steel increases, and the ability of hydrogen atoms to gather at the crack edges of the material increases.Nguyen et al[16] pointed out that the hydrogen embrittlement susceptibility of pipes depends on the hydrogen concentration in the hydrogen-doped natural gas, and with the increase of the hydrogen doping ratio and gas pressure, the hydrogen embrittlement susceptibility of high-grade pipeline steels continues to increase. Zhou et al[17] found that when X80 pipeline steel was stretched in hydrogen-doped natural gas, the loss of mechanical properties of notched specimens was significantly higher than that of smooth specimens, which indicates that when there are defects or cracks in pipeline steel, hydrogen doping of natural gas will lead to the rapid expansion of cracks and ultimately lead to the failure of the pipe, which may result in the risk of gas leakage and thus explosion. This shows that the size of the hydrogen doping ratio is one of the key factors leading to the occurrence of hydrogen failure.

3.3. Uneven Mixing

Localized gathering of hydrogen in the pipeline is one of the important hidden dangers that lead to hydrogen failure of pipelines, and whether or not layering occurs after natural gas doping is closely related to it. In order to avoid uneven distribution of hydrogen in natural gas pipelines after doping and resulting in hydrogen failure, relevant experts and scholars have studied the process of doping of hydrogen and natural gas through experiments or numerical simulations. Ren Shaoyun et al[18] simulated the injection of hydrogen into an air-filled confined space, and found that hydrogen would converge at the top of the tank, and there was an obvious hydrogen concentration gradient in the vertical direction inside the tank, indicating that hydrogen stratification occurred during the blending process. Based on Fluent software simulation, An Yongwei et al[19] studied the blending problem in T-shaped blending pipe and various variable-diameter blending pipes, and found that there is still obvious stratification of different gas components at the location of 35 times the length of the pipe diameter.

Hydrogen doping technology is also essential to avoid the phenomenon of hydrogen aggregation and stratification in hydrogen doped natural gas. Currently, there are two common ways to mix hydrogen and natural gas in pipeline transportation[20]: (1) directly injecting hydrogen into the natural gas pipeline without any mixing equipment; (2) utilizing gas-mixing equipment to mix natural gas and hydrogen sufficiently before injecting into the pipeline. For the gas mixing method without mixing equipment, the mixing is inefficient and the uniformity is insufficient. In order to improve the mixing efficiency, a variety of mixing technologies and equipment have been developed at home and abroad, such as venturi injection method, high-pressure proportionality adjustment method and flow rate proportionality adjustment method.

In summary, after hydrogen doping, natural gas and hydrogen are unevenly mixed within a short distance, and the distance required to achieve uniform doping is different for different hydrogen doping ratios. In addition to the uneven mixing may cause the hydrogen local concentration is too high, hydrogen-doped natural gas pipeline after stopping the phenomenon of gas stratification and hydrogen aggregation, there is no systematic research reports, which is one of the main basis for judging the risk of natural gas pipeline hydrogen-doped delivery, but also one of the pipeline maintenance must be considered as one of the safety issues.

4. CONCLUSION AND OUTLOOK

As an important hydrogen transportation method, natural gas pipeline hydrogen-doped transportation has received great attention from various countries and has a broad application prospect. In this paper, the following conclusions are drawn from the research and analysis on the development status of hydrogen-doped natural gas pipeline transportation at home and abroad, and the main factors affecting the safe transportation of hydrogen-doped natural gas pipeline, such as the change of the physical properties of hydrogen-doped natural gas, hydrogen failure and uneven mixing.

(1) Compared with natural gas, the changes in physical parameters of HNG have put forward new requirements for the equipment and process flow in the transportation process. Uneven distribution of hydrogen in hydrogen-doped natural gas pipelines leads to lower fracture toughness of the pipe, accelerating crack expansion and thus reducing service life.

(2) Due to the small density and easy diffusion of hydrogen, the risk of hydrogen-doped natural gas leakage and diffusion and combustion explosion increases. Taking into account the differences in natural gas pipes and working conditions, the development of natural gas hydrogen-doped transport in China needs to be combined with the actual situation, in a wide range of experimental research, pilot demonstration projects on the basis of promoting the use of. In view of the changes in the physical parameters of hydrogen-doped natural gas and leakage and combustion and other aspects of the new problems, it is still necessary to establish a special hydrogen-doped natural gas pipeline transportation standards and related regulatory policies to promote the development and application of hydrogen-doped natural gas pipeline transportation.

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