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REVIEW

Numerical Modeling of Hydrogen Concentration Fields, Flow Homogenization, and Leakage Dispersion in Hydrogen-Blended Natural Gas Pipelines: A Review

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ABSTRACT: The use of existing natural gas pipelines for hydrogen transportation has become a consensus in both domestic and international research. However, hydrogen and natural gas have significant differences in physical and chemical properties. After hydrogen injection and blending, concentration stratification or uneven spatial distribution may occur. When the pipeline leaks, the research object expands from the multiphase flow inside the pipeline to the gas migration and diffusion in the external environment. Numerical simulation technology has been widely applied in related research, but the existing research results have significant differences in physical models, boundary conditions, operating conditions, evaluation indicators, and verification methods. Currently, there is still a lack of systematic induction and horizontal comparison of numerical simulation methods. This study adopts a systematic literature review and comparative analysis method to summarize and compare existing research results, focusing on the hydrogen concentration distribution in the pipeline, the homogenization performance of static mixers and distillation devices, and the changes in the diffusion law of the gas concentration field after pipeline leakage. The review results show that the concentration distribution in the pipeline is mainly affected by the hydrogen blending ratio, flow state, pressure, temperature, hydrogen injection method, and pipeline geometric structure; the homogenization performance depends on the mixer structure, installation method, and operating conditions; the diffusion result of leakage is closely related to the internal pressure of the pipeline, the characteristics of the leakage outlet, the environmental wind speed, the degree of space limitation, and the soil properties. However, existing research has not yet formed a unified method in aspects such as turbulent models, component transport models, gas property processing, leakage source feature analysis, boundary condition setting, and verification process. This limits the direct comparison of different calculation results and their engineering application value. In the future, efforts should be strengthened in modeling research for complex conditions such as start-stop, pressure fluctuations, dynamic hydrogen injection, and transient leakage, conducting full-scale and multi-scale experimental verification and uncertainty analysis, and establishing unified evaluation indicators for concentration inhomogeneity, leakage influence range, and flow homogenization performance. These efforts will promote the concentration field research of hydrogen-mixed natural gas pipelines from qualitative pattern recognition to verifiable, comparable, and applicable for engineering decision-making, providing a methodological basis for pipeline operation safety assessment, flow homogenization strategy optimization, and leakage consequence prediction.

KEYWORDS: Hydrogen-blended natural gas; physicochemical properties; hydrogen concentration distribution; pipeline transportation; flow homogenization

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1 Introduction

Global industrialization and technological advancement have been primarily reliant on an energy infrastructure dominated by fossil fuels. Due to the escalating threat of the greenhouse effect, a transition to green and low-carbon energy sources is urgently required. Hydrogen, as a high-quality carrier of renewable clean energy, is recognized internationally as a crucial green energy source for future industrial development and an important component of the future energy system, owing to its advantages of being clean, zero-carbon, having high energy storage density (142 kJ/g), abundant sources, and vast reserves [1–3]. The release timeline of hydrogen energy policies in selected countries is illustrated in Fig. 1 [4–8]. Following the Paris Agreement, hydrogen energy policies have been gradually introduced in many countries, among which Japan initiated efforts in the hydrogen sector relatively early, with corresponding policies being released sooner [9–11]. In China, the release of hydrogen policy documents was relatively late; however, after their introduction, most provinces have formulated specific development roadmaps for hydrogen technology and plans for establishing a hydrogen industry chain [12]. Overall, most countries worldwide are continuously striving towards green energy transition and the development of a hydrogen industry chain, aiming to achieve green, low-carbon, and sustainable industrial progress and economic development in the new era.

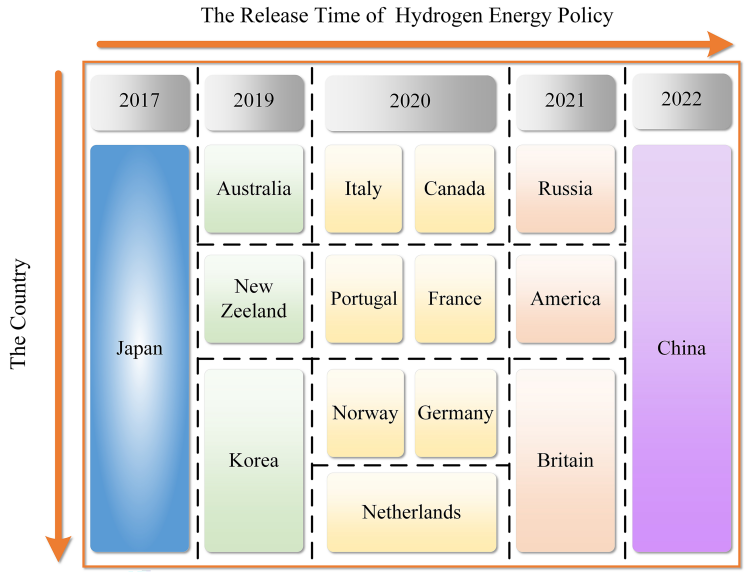


Figure 1: The release time of the hydrogen energy policy.

Hydrogen energy, as a crucial component of the energy architecture, forms an integrated upstream and downstream technology chain based on the four stages of production, storage, transportation, and utilization, thereby providing stable green and clean energy for industrial and civil development [13–15]. A schematic diagram of the entire hydrogen industry chain distribution encompassing "production, storage, transportation, and utilization," developed by the author based on the current state of hydrogen technology development, is shown in Fig. 2. Currently, global hydrogen production is derived from traditional fossil fuel-based hydrogen production, industrial by-product hydrogen, and electrolysis of water for hydrogen production, among which hydrogen production via natural gas steam reforming or partial oxidation accounts for a significant proportion [16,17]. Due to substantial equipment investment and low energy conversion rates, technological innovation in traditional large-scale natural gas hydrogen production has progressed relatively slowly. In recent years, with the growing demand for distributed natural gas hydrogen production technology, relatively more R&D investment has been directed toward small-scale hydrogen production technologies. Furthermore, various new technologies, such as direct hydrogen production via

photocatalysis and biomass hydrogen production, are rapidly developing as cutting-edge directions [18]. How to achieve large-scale, green, and low-cost hydrogen sources will be a key breakthrough direction for future hydrogen manufacturing. Owing to its unique advantages of being green and environmentally friendly, hydrogen energy has a wide range of applications. Common application scenarios include hydrogen energy storage, hydrogen fuel, synthesis of chemical feedstocks, and iron and steel smelting. The production of green hydrogen using wind and photovoltaic power can not only effectively utilize curtailed wind and solar power but also reduce hydrogen production costs, thereby enhancing grid flexibility while promoting the integration of renewable energy. As a hydrogen fuel, it can be used for power generation, hydrogen vehicles, gas turbines, and civil gas applications. Among these, solid oxide fuel cells, represented by companies such as Bloom Energy in the U.S. and Mitsubishi Heavy Industries in Japan, have achieved a certain level of commercial application. Japanese companies, led by Toyota, have iterated their hydrogen fuel cell vehicles to the second generation [19]. Companies such as Hitachi, Panasonic, and Toshiba in Japan have completed engineering validation for stationary pure hydrogen fuel cell systems [20]. Hydrogen used as a raw material can be synthesized into chemical products, such as ammonia and urea. Additionally, in the iron and steel smelting process, hydrogen can replace coke as a reducing agent for iron ore, thereby significantly reducing carbon emissions and the formation of harmful gases [21].

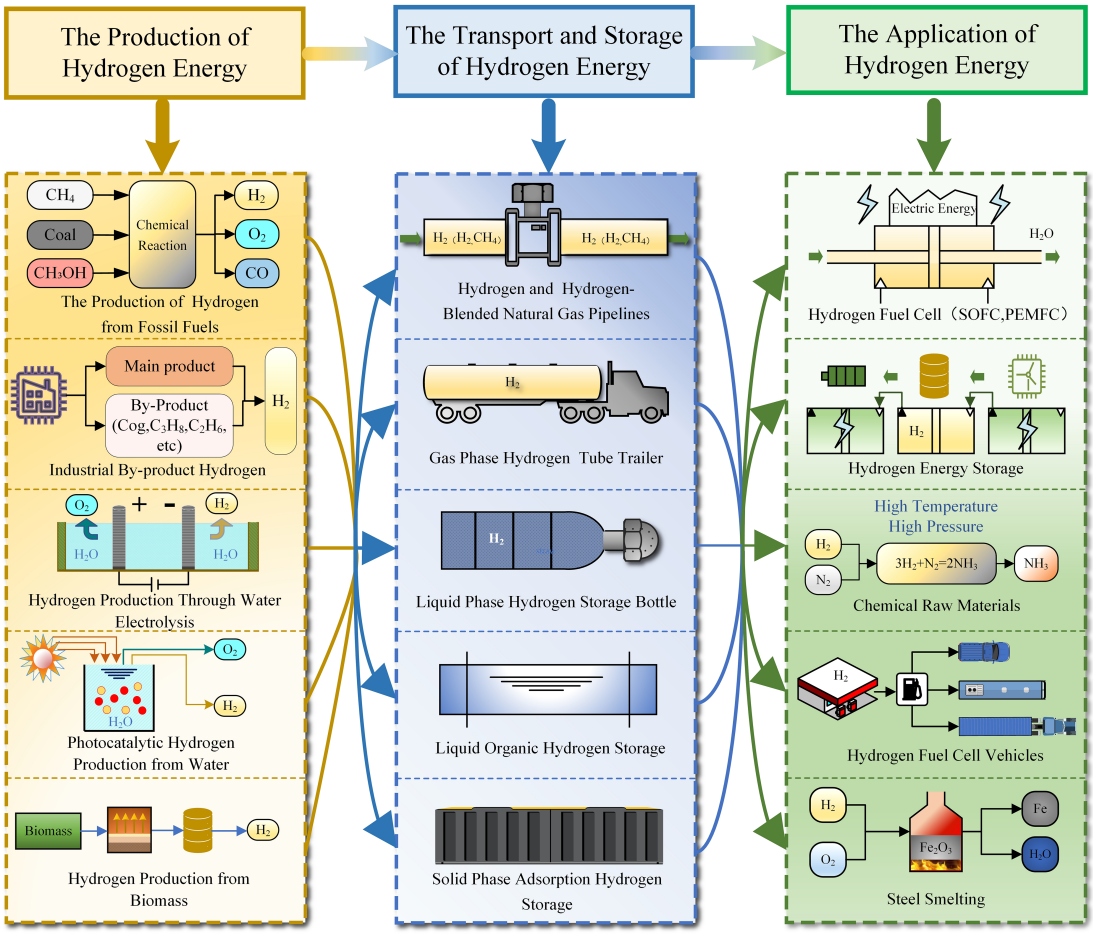


Figure 2: The distribution diagram of the whole industrial chain of hydrogen energy production, storage, transportation, and utilization.

Hydrogen storage and transportation technology, as a critical technical node connecting the upstream and downstream of the industrial chain, primarily includes high-pressure gaseous hydrogen storage and transportation, cryogenic liquid hydrogen storage and transportation, liquid compound hydrogen storage and transportation, and solid-state hydrogen storage and transportation [22,23]. Among the aforementioned methods, both pipeline hydrogen transportation and tube trailer hydrogen delivery fall within the category of high-pressure gaseous hydrogen storage and transportation technology, where hydrogen is stored as a high-density gas in pressure vessels through pressurization, ultimately enabling the transportation and utilization of hydrogen energy. Cryogenic liquid hydrogen storage involves cooling hydrogen to −253°C to liquefy it for storage and transportation [24]. Liquid compound hydrogen storage and transportation—such as liquid organic hydrogen carriers (LOHC), liquid ammonia, and methanol—is also a key focus in the hydrogen energy industry due to its advantages of high hydrogen storage capacity, high energy density, and safe storage and transportation. Currently, a consortium including Chiyoda has established a hydrogen supply chain based on the liquid organic hydrogen carrier model from Brunei to Kawasaki, Japan, achieving large-scale hydrogen transportation [25]. In addition, the solidification of hydrogen within materials using hydrogen storage materials to achieve highly safe and low-operational-cost hydrogen storage and transportation is also a future direction for technological development.

As shown in Table 1, the characteristics of current hydrogen transportation technologies are summarized. A comprehensive analysis of the advantages and applicable scenarios of various hydrogen transportation technologies indicates that blending hydrogen into natural gas for mixed transportation can avoid the large-scale construction of dedicated hydrogen pipelines, offering low technical implementation costs and high transportation efficiency, making it a promising pathway for large-scale hydrogen application [26]. Currently, the utilization of existing natural gas pipelines for hydrogen blending is widely adopted globally for hydrogen transportation [27–29]. Based on data analysis, the initial commissioning timelines of hydrogen-blended natural gas projects in selected countries and regions are plotted in this study, as specifically illustrated in Fig. 3. European countries initiated hydrogen-blended natural gas pipeline projects relatively early, while Japan was among the early adopters in Asia. Following the signing of the Paris Agreement, countries such as the United Kingdom, China, Italy, and Australia have also launched related projects and application research [30,31]. In future industrial development, hydrogen-blended natural gas pipeline transportation technology is expected to be adopted by more countries and regions, thereby advancing the global transition to green energy.

Table 1: Technical characteristics of hydrogen energy transmission.

Transport Phase State	**Gas Phase**			**Liquid Phase**		**Solid Phase**
Transportation mode	Long tube trailer transports hydrogen	Pure hydrogen pipeline transportation	Hydrogen-doped natural gas pipeline transportation	Low-temperature liquid hydrogen transport	Hydrogen transport by liquid compounds	Solid-state hydrogen transport
Technological superiority	The equipment is mature, the energy consumption is low, the hydrogen charging and discharging speed is fast, and the cost is low.	The transportation scale is large and the distance is long.	The conveying scale is large, the distance is long, and the cost is low.	High volume density of hydrogen storage.	The hydrogen storage volume density is high, and the storage and transportation process is safe and efficient.	Hydrogen storage has high volumetric density, low energy consumption, and good safety.

(Continued)

Table 1 (continued)

Transport Phase State	Gas Phase			Liquid Phase		Solid Phase
Technical disadvantage	Lack of transport capacity, the need for a large number of personnel deployment.	It is necessary to build new pipelines, and the cost is high.	The original natural gas pipeline has a hydrogen embrittlement damage problem.	There is a certain loss; the transportation cost is high, and it is difficult to transport over long distances.	The energy consumption of the operation is high, the operation is difficult, and there is a potential possibility of side reactions.	The transportation cost is high, and the charging and discharging efficiency of hydrogen is low.
Applicable scene	Hydrogen energy vehicle fuel.	Hydrogen energy automobile fuel, refining, city gas, etc.	Hydrogen energy automobile fuel, refining, city gas, etc.	Aerospace industry.	Hydrogen energy automobile fuel, refining, city gas, etc.	Hydrogen energy vehicle fuel.

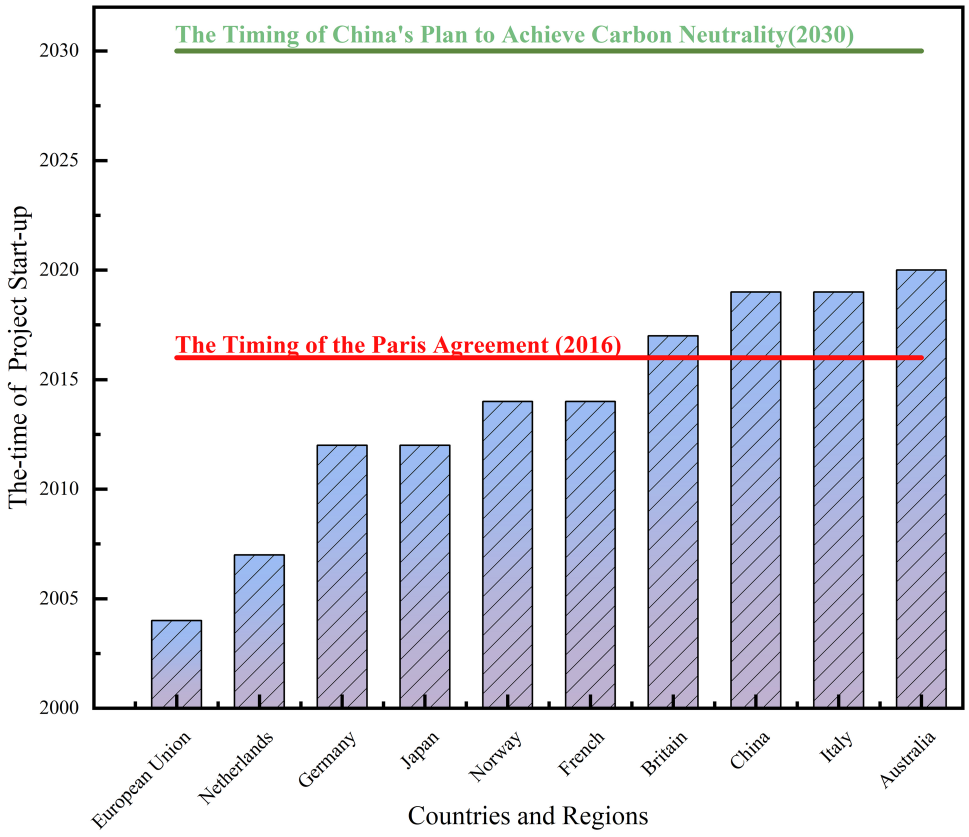


Figure 3: The starting time of hydrogen-doped natural gas projects in some international and regional regions around the world.

The hydrogen blending ratio in current global hydrogen-blended natural gas pipeline demonstration projects and related research projects generally ranges from 5% to 50%, with most countries maintaining a hydrogen blending ratio between 10% and 20% [32]. Most projects utilize existing natural gas pipelines to transport hydrogen-blended natural gas instead of building dedicated hydrogen pipelines. Therefore, the

concentration distribution of hydrogen in the pipelines directly affects the operational status of the existing pipeline system and the hydrogen content environment at different locations [33]. However, the performance evaluation of some pipeline materials usually assumes that the hydrogen in the transported medium is uniformly distributed. This assumption may not fully reflect the actual concentration differences that occur during hydrogen injection, transportation, shutdown, and leakage.

During the process of local hydrogen injection, differences in gas properties and inlet conditions may cause an uneven concentration distribution in the area where the natural gas main pipe is connected to the hydrogen injection branch pipe [34,35]. During the subsequent transportation process, the hydrogen concentration may also be affected by factors such as gas flow rate, pipe inclination, bends, valves, and other local structures. Under conditions of shutdown or low flow rate, concentration stratification may occur within the pipe; for local hydrogen injection structures and specific pipe sections, the mixed gas may need to travel a longer downstream distance before becoming uniform. These concentration differences will cause different pipe positions to be exposed to different hydrogen conditions, thereby increasing the uncertainty in the safety evaluation of pipeline materials. When a pipeline leaks, the research object further expands from the transport of internal components within the pipe to the gas diffusion in the external environment. The concentration distribution will also be influenced by factors such as the parameters of the leakage source, ventilation status, obstacles, soil properties, and the degree of space limitation.

Due to the limitations such as cost, safety risks, the number of measurement points, and the controllability of operating conditions in full-scale tests, numerical simulation has become an important means for studying the hydrogen concentration distribution inside and outside hydrogen-enriched natural gas pipelines. The CFD method can calculate the velocity field, pressure field, and component concentration field under different hydrogen blending ratios, flow conditions, pipeline structures, leakage parameters, and environmental conditions. The numerical method can also be used to compare and evaluate static mixers and other flow homogenization devices. However, the reliability of the calculation results still depends on the reasonable selection of physical models, gas property processing, turbulence and component transport models, boundary conditions, grid accuracy, and verification methods.

Based on this, this article conducts a review around three interrelated numerical research issues. Firstly, it summarizes the numerical and experimental studies on the stratification and non-uniform distribution of hydrogen concentration in the static state, straight pipe transportation, and special structural pipe sections and local hydrogen injection areas. Secondly, it summarizes the numerical studies on the leakage and diffusion of hydrogen-enriched natural gas in typical above-ground and underground scenarios, focusing on analyzing the concentration distribution after leakage and the influence of leakage parameters and environmental conditions. Finally, it reviews the CFD studies of static mixers and flow homogenization devices, including the geometric structure of the mixers, element arrangement, installation position, operating conditions, mixing distance, and pressure loss, and their effects on the homogenization performance.

Therefore, this article does not comprehensively discuss all the issues of hydrogen-enriched natural gas pipeline technology, but focuses on elucidating the application of numerical methods in the prediction of non-uniform concentration distribution within pipelines, the analysis of leakage diffusion, and the research on flow homogenization. The review highlights the numerical methods, calculation conditions, evaluation indicators, verification methods, and main conclusions adopted in existing studies, and then analyzes issues such as inconsistent model selection, idealized boundary conditions, insufficient transient condition research, limited full-scale verification, and the difficulty in directly comparing different research results. This article can provide numerical methods and theoretical guidance for understanding the hydrogen concentration distribution within hydrogen-enriched natural gas pipelines, evaluating the consequences of leakage diffusion, and improving the mixing performance within pipelines.

2 Mathematic Model

2.1 Governing Equation

Computational Fluid Dynamics (CFD) is based on fundamental physical laws such as conservation of mass, momentum, and energy. By making reasonable assumptions and mathematical simplifications of actual flow processes, complex fluid motions are transformed into systems of partial differential equations that can be discretely solved. During numerical simulation, physical effects such as viscous dissipation, turbulent fluctuations, heat and mass transfer, and local resistance can be quantitatively described using appropriate models. Combined with initial and boundary conditions, this enables the determination of spatial and temporal distributions of parameters such as velocity, pressure, temperature, and species concentration within the flow field. Therefore, the general form of the governing equations used is as follows [36–38]:

$$\frac{\partial(\rho\varphi)}{\partial t} + div(\rho U\varphi) = div\left(\Gamma_\varphi \text{grad}\varphi\right) + S_\varphi \tag{1}$$

where, φ represents a general variable; ρ represents the density of the fluid, kg/m^3; U represents the velocity vector of the fluid; Γ_φ representing the generalized diffusion coefficient; S_φ represents the generalized source term

(1) Continuity equation

The continuity equation is used to describe the conservation of mass during fluid flow processes and is one of the most fundamental governing equations in CFD numerical calculations. This equation is composed of variables such as fluid density, time, and velocity, indicating that the change in mass of any fluid element within a certain period of time is equal to the difference between the mass flowing into and out of that element. For flow regions without mass source terms, the mass within the fluid element will not be created or disappear out of nowhere. Its expression in the rectangular coordinate system is shown in Eq. (2) [39]:

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho\omega_x)}{\partial x} + \frac{\partial\left(\rho\omega_y\right)}{\partial y} + \frac{\partial(\rho\omega_z)}{\partial z} = 0 \tag{2}$$

where, t represents time, s; $\omega_x, \omega_y, \omega_z$ represents the components of velocity in the, m/s; If the fluid is in a steady state of motion, then (2) can be rewritten as:

$$\frac{\partial(\rho\omega_x)}{\partial x} + \frac{\partial\left(\rho\omega_y\right)}{\partial y} + \frac{\partial(\rho\omega_z)}{\partial z} = 0 \tag{3}$$

(2) Momentum conservation equation

The momentum conservation equation, also known as the Navier–Stokes equation, is the core equation that describes the laws of change in fluid velocity and pressure. According to Newton's second law, the rate of change of momentum of a fluid element per unit time is equal to the sum of the surface forces acting on the element, the volume forces, and the net momentum flux caused by the inflow and outflow of the element. Among these, the surface forces mainly include pressure and viscous stress, and the volume forces typically include external forces such as gravity. By solving the momentum conservation equation, the velocity field and pressure field of the fluid at different positions and times can be obtained. The mathematical expression is as follows [40]:

$$\frac{\partial(pu_x)}{\partial t} + \nabla(pu_x\bar{u}) = -\frac{\partial p}{\partial x} + \frac{\partial\tau_{xx}}{\partial x} + \frac{\partial\tau_{yx}}{\partial y} + \frac{\partial\tau_{zx}}{\partial z} + pf_x \tag{4}$$

$$\frac{\partial\left(pu_y\right)}{\partial t}+\nabla\left(pu_y\bar{u}\right)=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+pf_y \tag{5}$$

$$\frac{\partial\left(pu_z\right)}{\partial t}+\nabla\left(pu_z\bar{u}\right)=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+pf_z \tag{6}$$

where, p represents absolute pressure, Pa; $\tau_{xx}, \tau_{xy}, \tau_{xz}$ represents the component of viscous stress, Pa·s; f_x, f_y, f_z represents the unit mass force, m·s^{-2}.

(3) Energy conservation equation

The energy conservation equation is used to describe the laws of energy transfer and transformation during the fluid flow process. The change in energy within a fluid element is equal to the net flux of energy flowing in and out of the element, the work done by external forces on the element, as well as the effects of heat conduction, radiation, or other energy sources. Although energy can be converted among different forms such as internal energy, kinetic energy, and potential energy, the total energy of the system always satisfies the conservation law. Its mathematical expression is as follows:

$$\frac{\partial\left(pT\right)}{\partial t}+\frac{\partial\left(pu_xT\right)}{\partial x}+\frac{\partial\left(pu_yT\right)}{\partial y}+\frac{\partial\left(pu_zT\right)}{\partial z}=\frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{k}{c_p}\frac{\partial T}{\partial z}\right)+S_T \tag{7}$$

where, c_p represents specific heat capacity, J·mol^{-1}·K^{-1}; T represents the gas temperature, K; k represents the heat transfer coefficient, W·m^{-2}·K^{-1}; S_T represents the viscous dissipation term.

In CFD numerical simulation, the continuity equation, momentum conservation equation and energy conservation equation jointly form the basis for fluid flow calculation and provide necessary conditions such as velocity, pressure and temperature for the solution of the gas concentration field. On this basis, according to the research object, phase treatment method and model assumptions, component transport models or multiphase flow models can be further selected, and combined with state equations, turbulence models and diffusion models, the convective migration, molecular diffusion and turbulent mixing processes between hydrogen, natural gas and surrounding media can be described.

2.2 Turbulence Model

The flow during engineering transportation and leakage usually exists in a turbulent state, with its unsteady pulsation, vortex motion and energy dissipation strengthening the momentum and component transfer. Therefore, in the numerical study of hydrogen-enriched natural gas, the selection of the turbulence model not only affects the velocity field and pressure field, but also directly influences the prediction results of gas concentration distribution and mixing uniformity.

The turbulence calculation methods in Fluent mainly include zero-equation models, one-equation models, two-equation models, Reynolds stress models, and large eddy simulation. Among them, the two-equation model takes into account both the computational cost and the prediction accuracy, and is widely used in pipe transportation, gas mixing and leakage diffusion studies. Common models include Standard k-ε, RNG k-ε, Realizable k-ε, Standard k-ω and SST k-ω models [41].

The k-ε series models take turbulent kinetic energy k and dissipation rate ε as the solving variables. The Standard k-ε model has good convergence and low computational cost, and is suitable for fully developed pipe flow and weak separation conditions of conventional flows, but has limited adaptability to strong curvature, rotation and obvious adverse pressure gradients. The RNG k-ε model has better prediction ability for rotation, secondary flow, sudden expansion and jet impact, and is suitable for pipelines with bends, three-way valves and local components. The Realizable k-ε model has good applicability to jet diffusion, separation

flow and certain intensity of rotational flow, and can be used to describe the expansion of leakage jets and the mixing process between the inlet jet and the main flow.

The k-ω series models take turbulent kinetic energy k and specific dissipation rate ω as variables, and have good computational performance in the near-wall region. The Standard k-ω model is suitable for flows with obvious near-wall effects, while the SST k-ω model takes into account both near-wall prediction ability and far-field computational stability, and has good adaptability to adverse pressure gradients and separation flows. However, this model is sensitive to wall grids, and reasonable setting of boundary layer grids and the height of the first layer element is required during calculation.

Different turbulence models have differences in application scope, computational cost and prediction ability. Specific characteristics are shown in Table 2.

Table 2: Turbulence models and their characteristics.

Model	Key Feature	More Suitable Flow	Main Limitations
Standard k-ε	Good stability, low solution cost, and rich engineering experience	Fully develop pipe flow and ordinary high Reynolds number flows	Insufficient response to strong separation, rotation and significant curvature
RNG k-ε	Insufficient response to strong separation, rotation and significant curvature	Medium swirl, sudden expansion, secondary flow and impact jet	Even under strong rotation and highly anisotropic conditions, there are still limitations.
Realizable k-ε	Using a variable viscosity coefficient to meet certain stress constraints	Circular jet, flow around, gas mixing and moderate rotational flow	The accuracy near the wall depends on the wall treatment and the quality of the grid.
Standard k-ω	It can directly handle the near-wall area and is sensitive to the reverse pressure gradient.	Boundary layer, low Reynolds number flow and early separation problems	More sensitive to the turbulent parameters of free flow
SST k-ω	Combining the characteristics of the near-wall k-ω and the far-field k-ε	Separation flow, complex wall surfaces, bends and obstacle-induced flow around obstacles	High resolution is required for the near-wall grid.
Reynolds stress model	Consider the stress transport in different directions	Strong vortices, complex secondary flows and significant anisotropic flows	There are many equations, convergence is difficult, and the computational load is large.
Large eddy simulation	Analysis of large-scale unsteady vortex structures	Analysis of large-scale unsteady vortex structures	The grid requires a high level of computing resources.
Direct numerical simulation	Analyze all turbulent scales	Study of the basic mechanism at low Reynolds numbers	Difficult to be applied to engineering-scale problems

In conclusion, the flow of hydrogen-enriched natural gas involves multiple mechanisms such as wall shear, component diffusion, jet entrainment, density difference, and complex geometric disturbances. A single turbulence model is difficult to maintain optimal performance under all conditions. Model selection should serve the specific research objective: when focusing on overall transport and average concentration, an engineering-type two-equation model can be adopted.

3 Numerical Simulation of Hydrogen Concentration Distribution and Its Experimental Support

The detection and simulation research of combustible gas concentrations has a long-standing history, and its outcomes have been widely applied in industrial, civil, and scientific research domains. Since the

mixing of natural gas with hydrogen, hydrogen atoms are considerably smaller than those of traditional combustible gases such as methane, and the physical properties of the resulting gas mixture, including density, undergo certain changes compared to conventional natural gas. In addition, with the continuous construction and operation of hydrogen-blended natural gas pipelines worldwide, the application scenarios of gas concentration field detection technologies are also evolving. Both of these aspects present new challenges to existing gas concentration distribution detection and simulation techniques. Therefore, numerical simulation has become an important method for analyzing gas transport, mixing, and concentration evolution within pipelines. Experimental detection techniques are still necessary, as they can provide reference data for the interpretation, verification, and calibration of numerical results. Accordingly, this section primarily reviews numerical simulation studies of hydrogen concentration distribution, while detection technologies are discussed as complementary methods that support the evaluation of computational predictions.

3.1 Experimental Characterization of Hydrogen Concentration Distribution

In open, semi-open, and closed spaces, the characterization of gas concentration fields can be achieved using point-type sensors, multi-point sensor arrays, optical devices, or sampling analysis methods. These methods can measure local hydrogen gas concentrations and can identify the non-uniformity, accumulation, and diffusion behavior of the gas under specific operating conditions. Blokland et al. [42] developed a hydrogen-sensing chip capable of measuring hydrogen concentrations of at least 30 vol%, with an accuracy of approximately 0.1 vol%. Feng et al. [43] proposed a quartz tuning fork-based hydrogen sensor, achieving a detection accuracy of 0.74% for hydrogen in air and a precision error of 1.82%. Marangon and Carcassi [44] used oxygen sensors and gas chromatography. Gas diffusion experiments were conducted in a 25 m^3 enclosed area. The above research findings indicate that under different natural ventilation configurations, the concentration distribution of hydrogen is uneven. This suggests that the local geometric structure and ventilation conditions have a significant impact on the accumulation and diffusion of hydrogen.

Given that a single experimental detection method has certain limitations in terms of point layout, spatial coverage and temporal continuity, subsequent research can combine numerical simulation with experimental testing to obtain and analyze the spatiotemporal information of hydrogen transport, mixing and concentration evolution more comprehensively.

3.2 A Study on Numerical Simulation

Current research on concentration variations in hydrogen-blended natural gas mixtures is primarily conducted through macroscopic computational fluid dynamics (CFD) simulations and molecular dynamics (MD) simulations. However, both CFD and MD employ simplified assumptions in their studies and cannot fully capture the combined effects of gravity and Brownian motion/intermolecular forces on hydrogen-blended natural gas at the microscopic level [45]. For example, ANSYS Fluent software primarily analyzes from a macroscopic perspective, treating hydrogen and natural gas (mutually soluble) as two-phase flow, and lacks the supplementation of molecular thermal motion, resulting in the neglect of Brownian motion between gas molecules, which leads to significant computational errors. Furthermore, MD is limited by its computational scale and is only applicable to systems at nanoscale spatial dimensions and nanosecond temporal scales [46], rendering its application in large-scale hydrogen-blended natural gas systems insufficient. Peng et al. [47] used molecular dynamics simulations and analytical theory to study the equilibrium and diffusion behavior of hydrogen-methane mixture gases in a gravitational field, finding that stratification under gravity requires a substantial height difference, and low-temperature conditions also promote stratification. Consequently, some scholars have considered coupling CFD with MD [48,49], where MD provides intermolecular stresses and CFD handles the global fluid flow, thereby avoiding the

assumptions of CFD and extending the scale of MD. This coupling can preserve the balance between molecular gravity and Brownian motion, but its widespread application remains debatable. Moreover, some scholars have also pointed out that the hydrogen concentration distribution in hydrogen-blended natural gas mixtures should be strictly analyzed and demonstrated theoretically. Based on the thermodynamic principle of energy minimization, Li et al. [45] derived a mathematical model for the concentration distribution of hydrogen-blended natural gas under the influence of a gravitational field, and utilized the Peng-Robinson real gas equation of state for this mathematical model. Su et al. [50], based on the principle of minimum energy in thermodynamics and by integrating equations of state (EOS) for different gas conditions to calculate Helmholtz free energy and chemical potential, proposed a mathematical model to solve the concentration distribution of hydrogen-blended natural gas along the height direction under gravity in a shut-in pipeline. Tabkhi et al. [51] proposed a mathematical modeling framework for natural gas networks to study changes in energy transmission at different hydrogen blending ratios, identifying a maximum hydrogen blending ratio of 6%. Hafsi et al. [49] presented a mathematical model for the effects of hydrogen injection into natural gas networks, investigating the impact of hydrogen injection on natural gas flow, and found that hydrogen injection increases the pressure drop value within the pipeline and raises the gas flow velocity.

Currently, global research on hydrogen concentration fields is primarily focused on two core issues: hydrogen distribution scenarios and gas flow states, encompassing typical processes such as hydrogen static conditions, blending, straight-pipe transportation, and transportation through pipelines with special structures. Among these, high-pressure hydrogen storage and transportation vessels and pipelines with defects such as cracks are susceptible to hydrogen embrittlement, which may subsequently lead to major combustion or explosion accidents. Essentially, this is mainly attributed to the significant accumulation of hydrogen in localized areas, forming high-concentration zones that promote the entry of hydrogen atoms into the metal lattice. These atoms then interact with microscopic defects, ultimately triggering sudden fracture or crack propagation [52]. Therefore, conducting hydrogen concentration field distribution detection is crucial for effectively predicting and preventing hydrogen embrittlement failures, thereby ensuring the safe and reliable operation of hydrogen-blended natural gas pipeline transportation.

3.2.1 The Concentration Distribution of Gases in a Static State

As the foundation for studying the distribution patterns of hydrogen concentration fields, the concentration distribution of hydrogen in a static state must first be investigated to establish a theoretical basis for understanding its behavior under flowing conditions. Ren [53] simulated the process of injecting hydrogen into a sealed storage tank filled with air. The results showed that hydrogen preferentially accumulated at the upper part of the tank, and a distinct vertical concentration gradient was formed within the tank. Ban et al. [54] conducted a study on the hydrogen concentration distribution within urban hydrogen-enriched natural gas pipelines under different operating conditions. The results showed that a significant hydrogen stratification would occur after the pipeline was shut down. Liu et al. [55] employed computational fluid dynamics methods to study the volume fraction distribution of hydrogen-blended natural gas in stationary gas cylinders and shut-down pipelines. The results demonstrated that during static processes such as storage in gas cylinders and pipeline shutdown, hydrogen gradually rose to the top while methane sank to the bottom, leading to evident stratification.

In response to the component differences of vertical pipes, some studies conducted static experiments. Peng et al. [56] constructed two vertical static experimental pipes with a depth of 100 m each and diameters of 160 and 63 mm, respectively. The results showed that the hydrogen stratification phenomenon was more obvious in the smaller diameter pipe. Wu [57] verified through experiments that when natural gas and

hydrogen were mixed and placed statically in a vertical pipe, a concentration gradient would form, but the measured concentration difference was small.

Furthermore, some studies have utilized theoretical models or numerical methods to analyze the effects of geometric scale, hydrogen doping ratio, and thermodynamic models on the static concentration distribution. Ren and Zhang [58] analyzed the influence of pipeline diameter and hydrogen gas doping ratio on the stratification of hydrogen-doped natural gas in storage tanks. The results showed that the smaller the pipeline diameter and the higher the hydrogen gas doping ratio, the more likely the stratification phenomenon would occur. Su et al. [59] based on the principle of minimum energy, calculated the concentration distribution under conditions where the pipe diameters were 400, 600, 800 and 1000 mm, and the hydrogen concentration ratios were 1% and 20%. The results showed that although the hydrogen concentration changed along the direction of gravity, the change range was relatively small. Li et al. [45] combined the real gas state equation to simulate the component distribution of hydrogen-enriched natural gas at different altitudes. They also found that the hydrogen concentration changed relatively little with altitude. When the hydrogen enrichment ratio exceeded 50%, the concentration variation in a kilometer-scale pipeline exceeded 1%. Su et al. [50] further analyzed the extreme conditions that may occur during the transportation of hydrogen-enriched natural gas. The results showed that significant hydrogen stratification usually occurs under extreme conditions with a large elevation difference, such as an elevated pipeline with an elevation difference of up to 3000 m.

Overall, the existing experiments, CFD simulations, and thermodynamic model studies all indicate that under static conditions, the hydrogen concentration may change along the direction of gravity. However, the degree of stratification obtained by different studies is not consistent, and the results are related to the geometric dimensions of the pipeline or container, the hydrogen dilution ratio, the pipeline scale, the elevation difference, and the specific operating conditions.

3.2.2 Straight Pipeline Transportation Process

The straight pipe is the most basic and widely used form of pipeline in hydrogen-enriched natural gas transportation. Under continuous flow conditions, the relevant numerical studies mainly focus on whether hydrogen can be uniformly distributed along the pipeline and within the pipeline cross-section, as well as the influence of operating parameters such as flow velocity, pressure, temperature and hydrogen enrichment ratio on the concentration distribution.

Li et al. [60] used Fluent to analyze the flow characteristics of hydrogen-methane mixtures in horizontal pipelines. The calculation results showed that, between adjacent pressure changes, the hydrogen concentration remained basically stable around the initial value, with the maximum increase being 1.6%. Liu et al. [55] employed computational fluid dynamics methods to establish a hydrogen-blended natural gas mixing model and investigated the volume fraction distribution under straight-pipe flow conditions. It was found that when hydrogen-blended natural gas flowed at very low velocities, hydrogen gradually shifted towards the top of the pipeline, leading to stratification, which was more likely to occur under low-temperature and high-pressure conditions. Unlike the CFD studies that focus on local concentration fields, Guandalini et al. [61] developed a model to simulate the dynamic transportation of methane-hydrogen mixtures in pipelines and found that hydrogen blending resulted in changes in fluid density and velocity, reducing the energy transmission capacity. A hydrogen blending ratio of 5% caused a 0.1% drop in pipeline network pressure.

Overall, the existing numerical studies indicate that in some normal straight pipe transportation conditions, the hydrogen concentration can remain relatively stable; however, when the flow rate is low, concentration stratification may occur within the pipe cross-section. Nevertheless, due to the inconsistent research objectives, numerical models, operating conditions, and evaluation parameters among different studies, the relevant conclusions are still difficult to be directly compared.

3.2.3 Special Structure Pipeline Transportation Process

In the actual hydrogen-blended natural gas transmission system, special structures such as fluctuating pipes, bends, valves, and local hydrogen injection connection sections inevitably exist. Compared with straight pipes, changes in geometric shape and flow area will alter local velocity, pressure, and component distribution, resulting in varying degrees of hydrogen concentration deviations at different positions. Therefore, the existing studies mainly adopt three-dimensional numerical simulation to analyze the effects of pipeline structure, operating parameters, and hydrogen injection methods on local hydrogen volume fraction, concentration gradient, mixing length, and pressure loss. The relevant results can provide local flow field and concentration field information that is difficult to be fully characterized by experimental discrete measurement points. However, the physical property models, component transport methods, boundary conditions, and verification methods used in different studies still need to be further compared.

Cui [62] found that when hydrogen-blended natural gas flows in undulating pipelines, hydrogen stratification was more significant in the uphill sections compared to the downhill sections. When the flow velocity reached 10 m/s, uneven hydrogen distribution occurred only in the uphill pipe sections, while hydrogen distribution remained relatively uniform in the rest of the pipeline segments. Hydrogen-blended natural gas is suitable for low-pressure, high-velocity transportation. An [63] conducted research and found that when the inclination angle and pipe diameter were increased, hydrogen stratification was less likely to occur.

The research on bent pipes and valves mainly focuses on the influence of local geometric structures and operating parameters. Ban et al. [64] used numerical simulation to study the flow of hydrogen-enriched natural gas in bent pipes. The research results showed that under normal transportation conditions, the variation range of hydrogen volume fraction was approximately 0.2%; the calculation results were affected by pressure, flow rate, temperature, hydrogen volume fraction, and fluctuation angle. Xu et al. [65] conducted research and found that the pipe angle, elevation height, pipe diameter, temperature and the opening degree of the ball valve all affect the hydrogen concentration distribution; when the opening degree of the ball valve increased from 25% to 100%, the hydrogen volume fraction gradient increased to more than twice its original value. An [63] also found that when the opening of the ball valve increased, the stratification phenomenon became more pronounced.

The local hydrogen injection connection section is another type of important special pipe section. Current research mainly utilizes three-dimensional CFD models to compare structures such as T-shaped pipes, spiral pipes, and constricted pipes, and to analyze the effects of hydrogen injection ratio, injection angle, injection position, and mainstream velocity on the downstream gas concentration. Jia et al. [66] used numerical simulation software to analyze the influence of pipeline structure and hydrogen concentration ratio on the distribution laws of hydrogen concentration in the flow field and the velocity distribution of the mixed gas. The research results showed that when the hydrogen concentration ratio was 5%, the C-type mixing pipeline was the best model. Wang et al. [34] found that when the hydrogen concentration ratio increased from 10% to 20%, the hydrogen concentration in the middle and upper parts of the pipeline rose, and the stratification became more pronounced. Ouyang et al. [67] established a three-dimensional T-junction mixing model and found that stratification occurred when the Reynolds number ratio of hydrogen to natural gas (Re_hydrogen/Re_natural_gas) was less than 16.

The injection position, hydrogen injection direction, hydrogen gas flow rate, natural gas main flow velocity, and gas flow conditions all have an impact on the changes in the gas concentration field. Wu et al. [68] compared different hydrogen injection angles and the results showed that under their calculation conditions, injecting hydrogen at a 120° angle from the bottom of the pipeline could achieve better downstream concentration uniformity. Zhu et al. [69] found that compared with injecting hydrogen from the top or

bottom of the pipeline, injecting hydrogen along the axial direction of the pipeline requires a shorter distance to achieve a relatively uniform distribution. Khabbazi et al. [70] respectively used the ideal gas model and the Soave–Redlich–Kwong real gas state equation to simulate the hydrogen injection process in the T-shaped pipeline. The results showed that the mixing length required for vertical hydrogen injection at the bottom was approximately one quarter of that for horizontal hydrogen injection, and one fifth for vertical hydrogen injection at the top. This study also demonstrated the application of different gas state equations in the numerical simulation of local hydrogen blending processes. Eames et al. [71] conducted research indicating that bottom injection can facilitate the internal mixing of the fluid and reduce the hydrogen concentration on the lower surface of the wall. Fang et al. [72] pointed out that a lower hydrogen injection position and a smaller gas main flow rate can shorten the distance from the mixing point to the measurement section, but achieving complete mixing still requires at least 100 times the pipe diameter.

The turbulence models, component transport models, gas property treatments, boundary conditions, grid settings and verification methods used in the existing studies are not uniform. Therefore, it is still difficult to directly compare the results of different studies. Future research should conduct a systematic comparison of the concentration distribution and mixing distance predicted by different numerical models under similar geometries and operating conditions, in order to improve the reliability of the calculation results for hydrogen concentration fields in special structure pipe sections.

To summarize the typical concentration distribution issues discussed in Section 3.2, Fig. 4 presents the representative states and corresponding homogenization measures in the hydrogen-enriched natural gas pipeline system, including: (a) Static state of the gas, where density differences can easily lead to component stratification [55]; (b) Flow state in a straight pipe segment [73]; (c) Mixing and rectification devices, such as static mixers, designed to promote component homogenization [74]; (d) Special pipe sections like elbows, where complex flows can easily cause local hydrogen enrichment [64]. This schematic summarizes typical scenarios ranging from static conditions and transportation (straight pipes and special structures) to active flow rectification (mixers), visually reflecting the core aspects of hydrogen concentration distribution research and the necessity of implementing flow homogenization technologies.

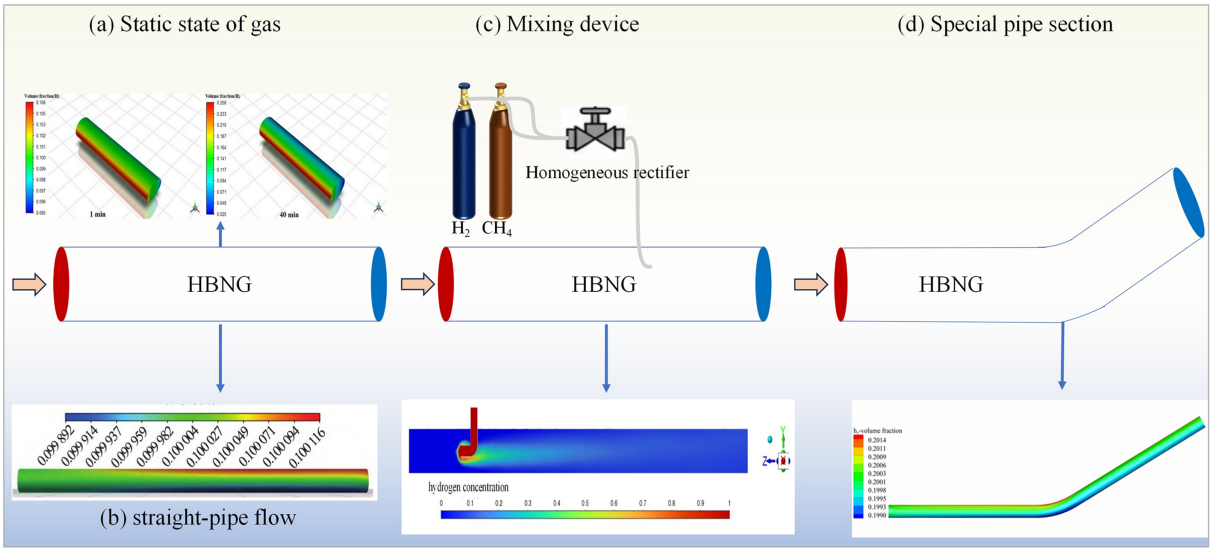


Figure 4: Typical states and rectification measures within a pipeline system.

4 Flow Homogenization Technology of Hydrogen-Doped Natural Gas Pipeline

Existing studies on internal transportation have shown that under different hydrogen injection methods, at lower flow rates, or in the presence of local disturbances, there may still be concentration gradients or component stratification downstream of the hydrogen injection joint; some numerical studies have also indicated that the mixed gas needs to pass through a relatively long downstream pipe section to become relatively uniform. Such non-uniform concentration distribution may cause different sections of the pipeline to be in different hydrogen-containing environments, thereby increasing the uncertainty in material safety assessment and pipeline operation analysis [37]. Therefore, how to actively reduce the concentration gradient and shorten the mixing distance has become one of the main problems that need to be solved urgently. Static mixers and other flow rectification devices can improve the concentration uniformity within a limited pipe section by changing the local velocity field, enhancing lateral transport and promoting the redistribution of components. However, conducting hydrogen adaptability tests on traditional mixing devices usually has a high economic cost, and it is difficult to obtain the velocity field, pressure field and component concentration field inside the device through experimental measurement points. Numerical simulation has gradually become an important means for evaluating gas mixing and flow rectification devices. Under unified inlet, outlet, wall and operation boundary conditions, the numerical model can quantitatively compare the flow characteristics, concentration distribution, mixing distance and pressure loss inside different device structures, and further analyze the influence of geometric parameters and operating conditions on the homogenization performance, thereby providing a basis for the design of prototype manufacturing and experimental testing, as well as the screening of structures, parameter sensitivity analysis and optimization design before the experiment.

Belhout et al. [75] explored the mixing characteristics of Newtonian fluids in the Kenics static mixer through numerical simulation. The results showed that when the Reynolds number increased or the fluid viscosity decreased, the shear effect generated by the mixing element intensified, and the mixing efficiency improved accordingly; however, an increase in fluid viscosity would also lead to a significant increase in system pressure loss. Zhou [76] conducted a comparison of various static mixers using Fluent. The results showed that the SX type had the highest pressure drop but the poorest mixing effect. Moreover, different types of mixers exhibited significant differences in terms of pressure loss, mixing length, and overall performance. Morales Ubal et al. [77] optimized the Kenics static mixer based on the discrete adjoint method. With only a slight increase in pressure loss, they significantly improved the uniformity of the mixed gas. Rahmani et al. [78] conducted a comparison of the performance and cost of SMX type and helical type static mixers based on numerical simulation. Qu et al. [73] constructed a Kriging surrogate model with smaller interpolation errors and combined it with the genetic algorithm to optimize the static mixer. After optimization, the uniformity index of the outlet section of the mixer increased by 7.2%, and the hydrogen-methane stratification phenomenon existing in the original structure was eliminated. Thus, it can be seen that numerical simulation is no longer limited to reproducing the mixing process, but can also be used to identify key structural variables and carry out multi-objective optimization based on indicators such as concentration uniformity, pressure loss, and device size.

Current research generally indicates that, compared with single operating parameters such as pressure and flow rate, the structure of the static mixer is the key factor determining the uniformity of gas mixing [79–81]. According to the relevant requirements of T/CAS 590—2022 “Technical specification for hydrogen-natural gas mixing station”, the static mixer used in the hydrogen-diluted natural gas station should ensure that the uniformity of the mixed gas is not less than 95% [82]. To meet this requirement, scholars both at home and abroad have focused on studying the effects of factors such as mixer type, geometric shape of mixing elements, number of elements, arrangement method, and installation position on the process of

hydrogen concentration redistribution. Su et al. [83] conducted a numerical study on the hydrogen-methane mixing characteristics in three static mixers (KSM, SMX, and LPD). The results showed that increasing the operating pressure, hydrogen mixing ratio, and flow rate could only slightly improve the mixing uniformity, while the structure of the mixing element was the dominant factor affecting the mixing effect. Huang et al. [37] proposed an improved static mixer (KSM). The research results showed that when the hydrogen concentration ratio was ≤20% and the flow velocity of the main pipeline was ≥1 m/s, the coefficient of variation (COV) decreased significantly from 346.30% to 7.95% within a range of 2 m. Kong et al. [84] conducted a study and found that when hydrogen and methane were mixed using the Kenics static mixer, the number and arrangement of the turbulence generating elements would affect the mixing performance. Liu et al. [85] conducted experiments to compare the performance of KSM type, S-shaped, orifice plate type, and Venturi type static mixers in the gas source natural gas mixing process. The results showed that the KSM type static mixer had the best mixing performance, and its blending effect was mainly influenced by two structural parameters: the axial length of the turbulence-creating blades and the rotation angle.

The component geometric parameters of other types of static mixers also have a significant impact on the flow field and concentration distribution. Cui et al. [86] conducted research and found that both the unit length L and the stagger angle θ of the SMV static mixer have a positive correlation with the turbulent kinetic energy of the flow field. Zhou et al. [87] pointed out that reducing the aspect ratio of the mixing chamber in the eddy current static mixer from 6 to 4 can significantly enhance the mixing efficiency. Ban et al. [74] used uniformity of mixing and pressure loss as evaluation indicators to analyze the performance of different structure hydrogen-blending mixers. The results showed that for the SK-type mixer, when the length of the deflector element was 750 mm, the thickness was 7 mm, the torsion angle was 180°, and the number of series stages was 3, its mixing performance was the best. Liu et al. [88] conducted a study on the mixing behavior of hydrogen and natural gas in the SMX static mixer by combining numerical simulation with experiments. The results showed that the number of mixing elements, flow conditions, and the hydrogen mixing ratio all affected the uniformity of the mixture. Under their experimental conditions, when using 4 mixing elements and the inlet gas velocity was 10 m/s, a relatively uniform gas dispersion could be achieved, which was considered to be a superior mixing scheme. Yang et al. [89] conducted calculations on five types of static mixer structures. The results indicated that the uniformity of hydrogen and natural gas mixing was jointly influenced by factors such as flow rate, hydrogen blending ratio, mixer type, ratio of mixer element length to width, twist angle, and number of elements. Increasing the twist angle and the number of mixer elements, as well as reducing the ratio of element length to width, all contributed to improving the blending effect. Among the studied parameters, the twist angle had the greatest impact. Among the compared structures, the new LPD static mixer had the best mixing effect, while the Y-shaped mixer had the worst effect. Di et al. [79] designed a new type of static mixer for the mixture of hydrogen and natural gas, and based on numerical simulation, analyzed the influence of structural parameters and flow parameters on the uniformity of mixing and pressure loss. Zheng et al. [90] proposed a coaxial shear static mixer with a ring-shaped cavity structure and used the CFD method to study the influence of different structural parameters on the performance of the mixer. When the number of cavities in the coaxial shear mixer increased to 48, the uniformity of hydrogen-gas mixture reached 95.43%, and the pressure loss was 67.02 Pa.

At present, the numerical analysis and structural optimization of the blending device have made significant progress, but there are still certain limitations. Firstly, most studies evaluate the performance of the mixer under the condition where the inlet velocity, pressure and hydrogen blending ratio remain stable. However, in the actual pipeline operation, pressure and flow fluctuations, changes in gas source load, and variations in hydrogen injection volume may cause the concentration field to be in a dynamic state. Secondly, the existing research mainly focuses on high-pressure or large-flow gas transmission

pipelines of industrial scale. Research on hydrogen blending in low-pressure and small-flow urban natural gas pipelines is relatively insufficient. The applicability and optimization potential of improved KSM and other compact mixers in such application conditions have not been fully studied. Therefore, subsequent research should combine transient numerical simulation, multi-parameter optimization and experimental verification, and focus on investigating the spatiotemporal evolution laws of hydrogen concentration under dynamic operation conditions.

5 Distribution of Hydrogen Concentration Fields during Pipeline Leakage

Under normal transportation conditions, the hydrogen-blended natural gas is constrained by the pipe wall and internal components. The concentration distribution of its components mainly depends on the inlet conditions, hydrogen blending method, flow state, and the local pipe component structure. When a pipeline leaks, the gas changes from restricted flow within the pipe to rapid release near the leakage hole and migration and diffusion in the external environment. It also undergoes processes such as pressure attenuation, expansion, jet suction, and turbulent mixing, resulting in a significant transient and spatially non-uniform characteristic of the hydrogen concentration field. The peak hydrogen concentration, concentration gradient, diffusion direction, and flammable concentration boundary after the leakage are not only affected by pipeline pressure, leakage hole size, hydrogen blending ratio, and leakage direction, but also closely related to the pipeline layout and external diffusion medium. Due to the limitations of factors such as high pressure, flammability, explosiveness, and uncontrollable leakage process, field tests usually can only obtain a small number of concentration data at measurement points, making it difficult to continuously characterize the complete three-dimensional transient concentration field. Numerical simulation can couple the internal leakage source, external flow, and component transport processes, predict the changes in hydrogen concentration at different positions over time, and obtain key parameters such as high concentration areas, explosion limit contour lines, and the maximum impact distance [91]. Therefore, this chapter focuses on the changing patterns of hydrogen concentration fields after pipeline leakage, and reviews the numerical research progress in typical scenarios such as above-ground and confined space, as well as buried pipelines. It particularly analyzes the effects of operating pressure, leakage hole characteristics, hydrogen blending ratio, environmental wind speed, and soil property parameters on the gas concentration distribution.

5.1 Typical Distribution of Hydrogen Leakage Concentration Fields in Above-Ground and Confined Spaces

When hydrogen-blended natural gas leaks from pipes, valves, flanges, and connection components, its concentration field is not only determined by the internal pressure of the pipe, the characteristics of the leakage hole, and the hydrogen blending ratio, but is also significantly influenced by the external space boundaries and air exchange conditions. According to the typical operating environment of pipeline facilities, existing studies mainly involve overhead pipelines and open station sites, valve rooms and compressor workshops, kitchens, etc., as well as indoor confined spaces at the end of urban gas distribution pipelines. Although different scenarios have differences in operating pressure, geometric scale and ventilation conditions, the research focus is on revealing the temporal and spatial changes of hydrogen and methane concentration peaks, component stratification, high-concentration areas and flammable concentration boundaries.

For overhead pipelines and open station sites, the leakage aperture, pipeline pressure, and release method determine the initial release intensity of the gas, which in turn affects the concentration level and spatial distribution near the leakage source. Peng et al. [92] employed numerical simulation to investigate the influence of various factors on the change of concentration patterns after gas leakage. The study revealed that an increase in pore diameter would lead to an increase in the gas concentration within the leakage area.

Within the specified working conditions, the influence of each factor on the concentration range was as follows: leakage pore diameter, wind speed, hydrogen blending ratio, and atmospheric temperature. After the wind speed increased, the high-concentration area gradually moved towards the downwind direction, and the vertical distribution height decreased accordingly. Tong et al. [93] pointed out that an increase in pipeline pressure would enhance the strength of the leakage source, increase the gas concentration near the leakage point, and push the boundary of the combustible concentration outward. Wang et al. [94] further investigated and found that the presence of buildings around the leakage area significantly alters the local flow path. There is a tendency for higher concentrations to occur between the windward side of the leakage outlet and the obstacle. Wall uplift and backflow on the leeward side may change the distribution characteristics of the concentration field in both the horizontal and vertical directions. In addition to the operating parameters, the form of the leakage source also causes differences in the near-field concentration distribution. Li et al. [95] employed numerical simulation to compare the diffusion process of gas concentration fields under different pipeline leakage sources. The results showed that the flow direction within the pipe and the outlet structure would alter the concentration attenuation characteristics near the leakage source. Among them, the orifice size had a particularly significant effect on the concentration changes in the jet centerline area. Based on this, the study established a prediction model for the maximum horizontal concentration influence distance using BPNN, providing a new method for the rapid estimation of pipeline leakage concentration ranges under multiple operating conditions.

In semi-enclosed or enclosed spaces such as station valve rooms, compressor workshops, and kitchens, the walls, roof, equipment layout, and leakage direction will further enhance the non-uniformity of the concentration field. Jia et al. [96] based on the modified Fuller model and Fick's diffusion law, established a multi-component diffusion coefficient model applicable within a certain hydrogen doping ratio range, and revised the component transport equation. Subsequent studies [97] showed that leaked gas usually migrates along the walls and roof and other boundaries first, and then gradually spreads towards the center of the space; at the same time, guidance suggestions were given on where to install combustible gas detectors, namely at a position 0.3 to 1.0 m below the factory roof. Li et al. [98] used numerical simulation software to analyze the influence of factors such as hydrogen concentration ratio, wind speed, and wind direction on the concentration field. The research results indicated that the migration of the gas concentration field was driven by buoyancy and the ambient wind, and the wind direction had a significant impact on the location of the high concentration areas. Jiang et al. [99] further demonstrated that at low wind speeds, buoyancy drives the accumulation near the source, while at high wind speeds, turbulent convective flow and horizontal advection dominate, reducing the concentration near the ground but enhancing the diffusion range in the downwind direction. Lv et al. [100] conducted research and found that the stratification of gas leakage inside the kitchen mainly occurs at the top, and as the height of the house decreases, the difference in concentration at the same level also decreases. To enhance the computational efficiency under complex stationery conditions, Li et al. [101] developed a high-fidelity plume concentration field prediction model based on adaptive leakage domains, thereby improving the efficiency and generalization ability of the limited high-fidelity CFD plumes.

5.2 Distribution of Hydrogen Gas Leakage Concentration Field in Buried Pipelines

After a leak occurs in the buried hydrogen-enriched natural gas pipeline, the gas undergoes release through the leakage hole, seepage through soil pores, and mass transfer at the underground-ground surface interface. Its concentration field is jointly controlled by the parameters of the leakage source, gas components, soil physical properties parameters, and external boundary conditions. Due to the strong concealment of the underground diffusion process, experiments can only obtain limited concentration changes at measurement points, while numerical simulations can continuously obtain the peak hydrogen concentration, contour

range, and its migration process over time. Therefore, it has become an important means for predicting the concentration field of leakage in buried pipelines.

Zhang and Zhao [102] conducted research and found that as the leakage time extended, the hydrogen concentration and the affected area continued to increase; increasing the pipeline pressure or enlarging the leakage aperture would enhance the leakage source strength, causing the high-concentration area to expand more rapidly towards the periphery of the soil and the surface. Liu et al. [103] further pointed out that both the pipeline pressure and the increase in leakage aperture would expand the hazardous concentration range in both the horizontal and vertical directions. Moreover, an increase in surface wind speed would reduce the vertical influence height of the gas cloud and promote its horizontal migration. Liu et al. [104] conducted a comparison of various conditions and concluded that the soil properties have the most significant control over the range of concentration fields. An increase in soil cover thickness will delay the arrival time of dangerous concentrations at the surface and reduce the surface diffusion area. The hydrogen blending ratio not only affects the leakage volume but also significantly alters the component concentration distribution of hydrogen and methane. Wang and Tian [105] conducted a three-dimensional numerical simulation and found that hydrogen and methane exhibited approximately “n”-shaped and “M”-shaped concentration distributions in the soil, respectively. Moreover, hydrogen still had a relatively high concentration at positions far from the leakage hole, indicating that the two components have different migration characteristics. Chang et al. [106] conducted research and found that when hydrogen-enriched natural gas diffuses in the soil, a concentration stratification occurs. As the hydrogen content ratio increases from 0% to 25%, the diffusion distance of methane increases from 1.46 to 1.52 m, indicating that hydrogen may have a carrying effect on methane. The experimental results of Zhu et al. [107] also demonstrated that hydrogen doping could enhance the diffusion of methane and shorten the time it takes to reach a stable concentration state. Peng and Luo [108] found that an increase in hydrogen content would lead to a decrease in the leakage volume of the mixed gas, an extension of the time required for the methane explosion lower limit contour to reach the surface, and a shortening of the time for the hydrogen explosion lower limit contour to arrive, indicating that the overall concentration of the mixed gas alone is insufficient to accurately reflect the hazards of different components. Bu et al. [109] conducted a study based on the concentration of gas reaching the lower limit of the explosion threshold. They found that increasing the hydrogen content ratio, pipeline pressure, and leakage aperture would all expand the range of the farthest dangerous concentration. Among these, the influence of pipeline pressure was the most significant. Bu et al. [110] conducted research and found that after hydrogen addition, the pressure, velocity and concentration distribution ranges in the soil all increased. When the hydrogen addition ratio increased from 0% to 30%, the radius of the explosion hazardous area expanded from 1.523 to 1.612 m. Liu et al. [111] conducted research and found that although the quality leakage of hydrogen-enriched natural gas might be lower than that of pure natural gas, its underground hazardous radius and above-ground hazardous height would still increase. Wang et al. [112] believe that an increase in hydrogen doping ratio will reduce the rate of mass leakage and shorten the leakage time. The initial pressure of the pipeline mainly controls the leakage intensity and the temperature change within the pipe. Therefore, the influence of hydrogen doping ratio on the concentration field needs to be comprehensively considered, taking into account the leakage source strength, component diffusion rate, explosion limit, and the duration of dangerous concentration. The pore structure and permeability of the soil determine the main diffusion channels for the leaked gas. Sandy soil has larger pores and better connectivity, and the gas diffusion speed and influence range are usually higher than those of loam and clay. Ban et al. [113] found after incorporating the measured heterogeneous parameters of the backfill soil into the leakage model that the horizontal diffusion range in the heterogeneous backfill soil was 0.44 m greater than that of typical loam soil and 0.28 m greater than that of sandy soil, indicating that the assumption of homogeneous soil might

underestimate the lateral diffusion within the actual pipe trench. Lu et al. [114] further research indicates that when the leakage point is located within a confined space such as a brick-lined trench, the gas will quickly fill the local space, and the leakage aperture, pipeline pressure, leakage position and direction will change the location of the high-concentration area and the duration of the combustible concentration. In addition to the concentration field, the temperature change caused by the leakage can also be used as an auxiliary detection basis. Zhu et al. [115] discovered through experiments and numerical simulations that as the hydrogen doping ratio increased, the temperature drop near the leakage point and the effective detection range of the optical fiber sensor both increased, indicating that the temperature field can be used to indirectly identify underground leaks. Mohanty et al. [116] verified the predictive capability of the CFD model for the transient migration of gas in the sand layer, the breakthrough to the surface, and the arrival of gas at the lower limit of the explosion through experiments.

Based on the existing research results, it can be concluded that different pipeline layout forms have their own specific numerical research focuses. For overhead pipelines, the coupling effect of wind fields and obstacle-induced vortices should be emphasized; in the buried scenario, the soil pore structure, soil cover thickness, and the connection between the underground and above-ground areas should be highlighted. Although the hydrogen blending ratio, operating pressure, and leakage hole parameters play important roles in all scenarios, the influence degree of these factors will vary with different environmental boundaries and calculation models. Therefore, subsequent research should strengthen the horizontal verification among different numerical methods and improve the reliability of accident consequence prediction through full-scale experiments, grid sensitivity analysis, and parameter uncertainty evaluation.

6 Conclusion

Utilizing existing natural gas pipelines for hydrogen-enriched transportation is an important technical path for achieving large-scale and long-distance transportation of hydrogen. This paper focuses on the hydrogen concentration field issue of hydrogen-enriched natural gas, systematically reviewing the numerical studies on the concentration distribution within the pipeline, the flow homogenization of static mixers and rectifiers, as well as the external diffusion after pipeline leakage. The paper also compares the numerical models, boundary conditions, operating parameters, evaluation indicators and verification methods adopted in existing studies. The main conclusions are as follows:

(1) The hydrogen concentration field inside the pipeline is jointly influenced by factors such as hydrogen addition ratio, flow state, pressure, temperature, hydrogen injection method, and pipeline geometry. Existing numerical studies have shown that concentration stratification or uneven spatial distribution may occur in situations such as pipeline shutdown, low flow rate, fluctuating pipe sections, local geometric disturbance areas, and downstream of the hydrogen injection joint. The concentration field results are also highly sensitive to the setting methods of inlet velocity, mass flow rate or pressure, outlet boundary, wall treatment, and initial concentration field. Therefore, in subsequent research, dynamic hydrogen injection, pipeline start-stop, pressure fluctuations, and time-varying leakage processes should be strengthened in modeling, and full-scale pipeline numerical studies should be gradually carried out.

(2) Static mixers and other flow rectification devices can reduce local concentration gradients and shorten the downstream distance required for the mixture gas to reach a relatively uniform state. Their homogenization performance is affected by the geometric structure of the mixer, the number and arrangement of components, the installation position, hydrogen addition ratio, and flow conditions. However, the improvement of concentration uniformity usually comes with additional pressure loss. Therefore, in subsequent research, multi-scale experimental verification, uncertainty analysis, and parameter sensitivity evaluation should be strengthened to establish a unified concentration non-uniformity, mixing performance, and pressure loss.

(3) When a pipeline leaks, the concentration field problem shifts from confined transport within the pipe to transient migration and diffusion in the external environment. The gas is affected by factors such as pipe internal pressure, leakage aperture and direction, hydrogen addition ratio, environmental wind, ventilation conditions, degree of space limitation, soil thickness, and soil properties. At the same time, different leakage source treatment methods such as constant pressure, fixed mass flow rate, and time-varying pressure attenuation can also lead to significant differences in peak concentration and gas range prediction results. Therefore, in subsequent leakage-related research, supplementary verification with experiments should be strengthened to further validate the applicability of the research results and establish leakage impact range evaluation indicators.

(4) Numerical simulations can obtain velocity fields, pressure fields, and component concentration fields that are difficult to be fully characterized by discrete experimental measurement points, and are important means for studying the redistribution of hydrogen gas, flow homogenization, and leakage diffusion within the pipeline. However, existing studies have not yet formed unified norms in aspects such as turbulence models, component transport models, boundary conditions, calculation scales, evaluation standards, and verification procedures, which limits the direct comparison of different results and their engineering applicability. Some studies also mainly focus on idealized geometries, steady-state conditions, and limited parameter ranges, and do not adequately consider the complex dynamic processes in actual pipelines.

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