Review of Hydrogen Fuel Cell Vehicles

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Abstract. As a new energy vehicle, the hydrogen fuel cell vehicle has the characteristics of zero-pollution and zero-emission, which has attracted widespread attention from all over the world. At the same time, various problems encountered in the application of hydrogen energy need to be resolved urgently. The article mainly analyses the current hydrogen production emissions and the leakage of hydrogen fuel cell vehicles. This article first analyses the principles and emissions of traditional and new hydrogen production methods, and then analyses the current research status of hydrogen fuel cell vehicle leakage through a combination of various theoretical and experimental studies, and proposes reasonable suggestions for future research directions.

Key words: Fuel cell vehicles, Emission, Safety, Leakage.

1. Introduction

Hydrogen energy has many advantages such as high combustion calorific value, high energy density, good environmental performance, wide sources, diverse utilization, convenience in storage and transportation, and so on. Hydrogen fuel cells can make full use of their advantages and can be applied to many fields, such as energy storage, power generation, and automobiles. HFCV (Hydrogen Fuel Cell Vehicle) has been valued by many countries, and many hydrogen application plans and policies have been introduced in the last century. Several HFCV models such as Mirai, Clarity, and NEXO produced in some factories are already on the market. However, technical issues that affect daily use are important to the government and customers.

This article reviews the technical problems encountered in the use and production of hydrogen fuel cell vehicles that hinder the application of hydrogen fuel cell vehicles in the civil field. The problems are mainly in the production of hydrogen and the car itself.

For hydrogen production, the current industrial hydrogen production mainly uses methane gas to produce hydrogen and electrolysis of water to produce hydrogen. However, hydrogen production from methane gas will produce carbon dioxide, and water electrolysis technology may cause excessive energy consumption. The most ideal method should be to produce hydrogen from renewable energy sources such as solar energy and biological energy, but the current technology has not yet reached it. As for hydrogen storage, the early experimental studies mainly focused on the subsonic jet flow with a pressure ratio lower than the critical pressure ratio. The model used was evolved from the model established by the early study of the flow and diffusion process of pollutants when discharging sewage. An important method for the research of high-pressure underexpanded jets is to simulate the gas flow in the far-field by using the "virtual nozzle model", which can ignore the complex shock structure in high-pressure underexpanded jets, so as to reduce the difficulty of research. And we summarize some deficiencies in experimental research, theoretical modeling, and numerical simulation, and put forward relevant suggestions. In addition, this article also briefly discusses the research progress of hydrogen leak-related fault diagnosis technology.

The remainder of this paper is organized as follows. Section II surveys the emission that occurs in the production of hydrogen and the state-of-the-art in it. Section III discusses the safety of hydrogen fuel cell vehicles. Section IV describes the fault diagnosis. Section V concludes.

2. Analysis of Hydrogen Production

2.1. Issues of Emission during Manufacture of Hydrogen

In hydrogen cells the overall reaction is

$$H_2 + \frac{1}{2}O_2 = H_2O \tag{1}$$

It seems that hydrogen cells only produce water that is absolutely environmentally friendly when we use it. Yet what we need to know is that hydrogen is a kind of secondhand energy rather than primary energy. Emission comes into being when hydrogen is produced [1]. When we produce hydrogen, quite a lot of greenhouse gases and harmful gas come into being. We have two traditional kinds of principal methods of hydrogen manufacture, thermochemical cycle, and electrochemistry. These general methods can be classified into some specific methods, hydrogen from coal, hydrogen from natural gas, shift reaction of carbon monoxide, and electrolysis of water. Hydrogen from marsh gas most emission of CO_2 and highest energy consumption, marsh gas with carbon capture and storage is better than marsh gas only, and electrolysis and biogas are most economical and environmentally friendly [2].

2.2. State-of-the-Art of Hydrogen Production

A) Improvement of Traditional Methods

1) Electrolysis of Water

Four methods of water electrolysis are compared by Hong Mei Yu et al. [3]. There are some major methods of electrolysis of water, AWE (Alkaline Water Electrolysis), PEM (Proton Exchange Membrane that is mainly used for hydrogen cell), AEM (Solid Polymer Anion-exchange membrane electrolysis), and SOE (Solid Oxide Electrolysis).

Hong Mei Yu's conclusion shows that AWE is most harmful to the environment, yet PEM and AEM are not harmful to the environment. And now AWE is most widely being used. So we are suggested to accelerate the speed of industrialization of PEM and AEM. This thesis considered the comparison of these four methods yet it did not analyze their mechanism.

2) Improvement of Hydrogen from Natural Gas

During the process of hydrogen from natural gas the most significant issue is the emission of CO_2, so how to transform CO_2 into energy should be thought about.

Liu Yang et al. [4] put forward a method that we can transform CO_2 into methyl alcohol and glycol. They discuss the technology of transformation of CO_2 and analyze its economic benefit.

B) Environmentally Friendly New Methods

1) Hydrogen by Water Photolysis

Electrolysis of water is high efficiency. However, electric energy itself is a secondary energy source. Photolysis of water use optical energy rather than electric energy, which is primary energy.

TiO_2 single crystal has the ability to let water decompose by solar rays. And its reaction equations are,

$$TiO_2 \rightarrow TiO_2\,(e^- + h^+) \tag{2}$$

$$2e^- + 2H^+ \rightarrow H + H \rightarrow H_2 \tag{3}$$

$$h+ + OH- \rightarrow \cdot OH \tag{4}$$

$$\cdot OH + \cdot OH \rightarrow H2O + 1/2\ O_2 \tag{5}$$

There are many kinds of metallic oxide catalyzers such as CuO, ZnO, and TiO_2.

DaiMan et al. [5] have summarized the application of different structures of TiO_2. TiO_2 has many advantages and is widely used for hydrogen production, besides, TiO_2 has many types of structures like nanofiber and nanotube. Their structures have been researched and their characters and functions have been discovered. Furthermore, TiO_2's ability to photocatalysis can be promoted by adulteration.

Yet these researches have not been compared to filtrate the best method in Dai's thesis, furthermore, cost and environmental benefit are not analyzed when these catalysts are being produced causes lacking in methods and deeds to transform experimental findings into practice results.

2) Biological Hydrogen Production

Biological hydrogen production includes photosynthetic hydrogen production and fermentative hydrogen production in general. Both of them make use of bacteria to produce H_2. To make biological hydrogen production workable, there are 2 essential issues, biological activity, and cost control.

Chinese Academy of Sciences has research on biological hydrogen production, which gives some valuable data and advice [6]. The definition of coupling is a phenomenon where one reaction is processing, other reactions accompanied it in the relation of chemometrics. Hydrogen production efficiency can be dramatically promoted by the use of darkness-light coupled reaction, so that dark fermentation and light fermentation are complementary with each other.

Dark fermentation:

$$C_6H_{12}O_6 = C_3H_7COOH + 2\ H_2 + 2\ CO_2 \tag{6}$$

Light fermentation:

$$C_3H_7COOH + 6\ H_2O = 10\ H_2 + 4\ CO_2 \tag{7}$$

Overall reaction:

$$C_6H_{12}O_6 = 6\ CO_2 + 12\ H_2 \tag{8}$$

This research has discussed how to promote the efficiency of hydrogen production and gives some useful methods, it analyzed different operations' influence on the production of hydrogen and concluded that darkness-light coupled reaction is beneficial to hydrogen production. Besides, the Harbin Institute of Technology [7] evaluates the influence on sludge fermentation to produce hydrogen by different pretreatment and then compared several kinds of pretreatment and drew a conclusion of those pretreatments' advantages and disadvantages. Each pretreatment has its advantages and disadvantages, so properly making use of them is significant.

3. Study on hydrogen leakage of fuel cell vehicle

High-pressure gaseous compressed hydrogen storage is currently considered the most widely used and most mature hydrogen storage technology, it is also the very method being applied most widely in the field of fuel cell cars [8]. However, gaseous hydrogen storage brings some potential safety hazards to the use of hydrogen. When hydrogen is used as an energy carrier, due to its own physical and chemical properties, it presents a dual character of both security and insecurity. Hydrogen has the characteristics of low density and good diffusibility, making the burning mixture not gather on the bottom when hydrogen cell divulges and hydrogen is ignited [9], which aids security. **Table 1** shows that hydrogen has the most widely flammable range, the fastest flame speed, and the lowest minimum ignition energy in the air, which is not good for security. In addition, hydrogen has the characteristics of hydrogen embrittlement, leakage (The leakage per unit time is about 1.3-2.8 times that of methane [10]), and explosiveness [11]. During the normal operation of fuel cell vehicles, hydrogen storage systems, transportation systems, and fuel cell systems may all cause some safety problems due to equipment rupture and hydrogen leakage [12].

Table 1. Important properties of hydrogen and comparison with traditional fuels [13]

Characteristic	*Hydrogen*	*Natural Gas*	*Gasoline*	*Significance*
Heating value (MJ/kg)	120	50	44	higher heating value
Flammability limits in air (vol%)	4-74	5-15	1-7	wider limits
Density (kg/m3)	0.082	0.67	4.4	lowest density
Diffusion coefficient in air (cm2/s)	0.61	0.16	0.05	faster spread
Stoichiometric flame speed (m/s)	2.1	0.4	0.3	faster burning
Minimum ignition energy in air (ml)	0.02	0.3	0.3	easier ignition

3.1. Hydrogen safety accident of fuel cell vehicle

Hydrogen safety accidents often start with hydrogen leakage [14-16]. According to the specific situation, hydrogen leakage can be divided into continuous release and instantaneous release. After that, flash fire, jet flow fire, detonation, or even explosion may occur in different conditions as shown in **Figure 1**. Different accidents cause different damage to the human body, mainly including asphyxia, frostbite, burn and impact injury [10,17], which are often nonfatal injuries. They will cause damage to property and equipment most of the time.

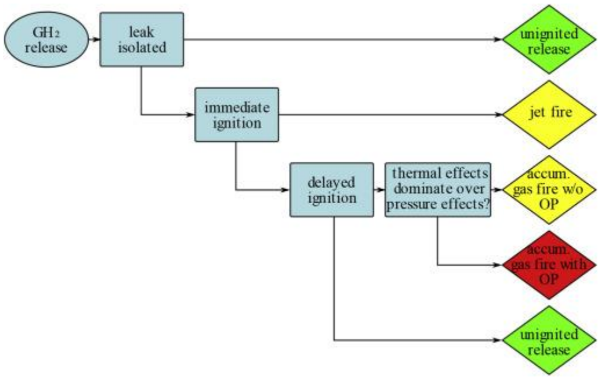

Figure 1. The possible scenarios that could occur after a hydrogen release [18]

According to the different spaces, accidental leaks from high-pressure hydrogen storage tanks can be divided into open spaces and closed spaces. When hydrogen leaks in an open space, the hydrogen will rapidly diffuse into the air with buoyancy. When a leak occurs in a confined space such as a garage, hydrogen is more likely to accumulate, and quickly mixes with air to become a flammable mixture, thereby forming a wide range of flammable ranges [19]. Severe accidents like jet flow fires or explosions will be more likely to occur. The overpressure and heat radiation generated after the explosion will cause serious injury to the surrounding personnel and equipment. This section will discuss research progress on hydrogen leakage of fuel cell vehicles under various conditions.

3.2. Theoretical research

A) Subsonic jet

When gas leaks from the outlet, it can be roughly divided into two flow states according to the difference between the leakage pressure and the critical pressure: under-expanded jet and subsonic jet. In the process of subsonic leakage, the outlet pressure of hydrogen is equal to the ambient pressure, and the flow rate is relatively low. It may occur in pipeline connections, welds, and valves of hydrogen storage and transportation equipment, such as the leakage of low-pressure electrolyzers, hydrogen storage tanks, pipe fittings, and sealing rings. In the serious hydrogen leakage accident of fuel cell vehicles, the under-expanded jet plays a leading role. However, due to the strong diffusion and flammability of hydrogen, subsonic leakage is also dangerous. The early study of subsonic leakage is of great significance for the subsequent study of underexpanded jets.

In the study of subsonic jet, Froude number is usually used to describe the proportional relationship between inertial force and buoyancy in the jet process. Froude number is defined as [20],

$$Fr = \frac{u_e}{\sqrt{\frac{g d_e(\rho_\infty - \rho_e)}{\rho_e}}} \tag{9}$$

In the past, an integral model of low-pressure leakage was established to predict the mobility and concentration diffusion of pollutants in the process of industrial wastewater discharge [21,22]. After that, the integral model was popularized and applied to more occasions, including the research on gas jets [23,24]. This model provides certain theoretical support for the calculation of hydrogen leaking jets. Winters [25] made use of Hirst's [26] empirical equation in the integral model to calculate the entrainment rate of the jet to the air, which took advantage of conservation of mass and momentum to calculate the characteristic width of the initial segment of the jet. After that, Houf et al. [27] used the same integral model as Winters' to calculate the subsonic hydrogen jet with a Froude number of 99~268, and compared the experimental measurements and calculations based upon the model of the hydrogen mole fraction along the centerline of the jet. The two results are very close. This experiment was repeated by EI-Amin et al. [28], who found that when Fr is not less than 152, the model calculation value of jet width is significantly lower than the experimental results of Schefer et al., as shown in **Figure 2**. Besides, El-Amin et al. [29,30] used CFD simulated results to compare with calculation results. However, they did not solve the problem that the calculated value of jet width is relatively low. Now that the model has been continuously improved to be used specifically for the calculation of low-pressure hydrogen jets. This model includes basic equations such as mass, momentum, and energy conservation equations.

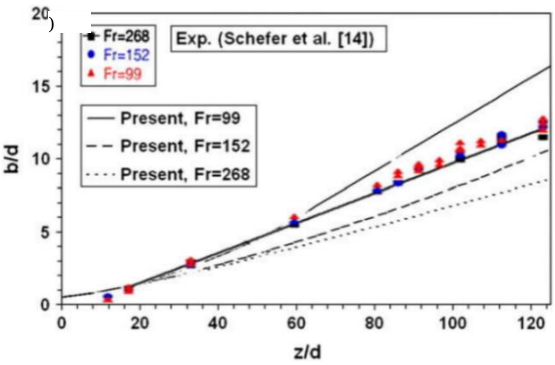

Figure 2. Comparison of the current model and experiments by Schefer et al. of the jet width. [31]

In view of the self-preservation behavior of the distribution of the jet gas parameters such as speed, temperature, and concentration, many researchers have conducted a study of the concentration attenuation along the centerline of the jet during different gas jet processes [32-34]. The researches show that once the equation of density ratio and nozzle diameter taking dimensionless axial distance is building, in the jet area dominated by the initial momentum, the mass fraction attenuation of various gases can be expressed by the following formula:

$$\frac{Y_e}{Y_{c1}} = C_d \frac{z}{d_e\sqrt{\frac{\rho_e}{\rho_\infty}}} \tag{10}$$

B) High-pressure under-expanded jet

The critical pressure of hydrogen is 0.19MPa. The storage pressure of hydrogen in high-pressure hydrogen storage tanks on the vehicle and high-pressure hydrogen pipelines is much higher than the ambient pressure. Therefore, the hydrogen leakage process of the high-pressure hydrogen storage container is actually a typical highly under-expanded jet process. The under-expanded jet is of great significance to the study of accidental hydrogen leakage.

For theoretical research on the high-pressure supersonic jet, the low-pressure leakage integral model cannot be used directly considering the relatively complex physical field at the leakage port. The general approach is to simplify the problem of high-pressure underexpanded jet into a low-pressure leakage problem with the same mass flow rates through the virtual nozzle model, so as to reduce the complexity of jet shock and improve the calculation efficiency. At present, many scholars have proposed effective virtual nozzle models, as shown in **Table 2**.

Table 2. Virtual nozzle model of some scholars

researchers	Diameter of virtual nozzle	boundary conditions
Birch et al.[42]	$\frac{d_{ps}}{d_e} = \sqrt{\frac{P_T}{P_s}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\gamma-2}}\sqrt{\frac{T_s}{T_T}}}$	$P_n = P_\infty, T_n = T_\infty,$ $u_n = c_n$
Birch et al.[43]	$\frac{d_{ps}}{d_e} = \frac{\rho_e u_e}{\sqrt{\rho_{gas}(P_e - P_s + \rho_e {u_e}^2)}}$	$P_n = P_\infty, T_n = T_\infty$
Ewan et al.[44]	$\frac{d_{ps}}{d_e} = \sqrt{\frac{P_e}{P_s}}$	$P_n = P_\infty, T_n = T_e,$ $u_n = c_n$
Yuceil et al.[45]	$\frac{d_{ps}}{d_e} = \sqrt{\frac{2n(\gamma Ma_e)^2(\gamma+n-1)-(\gamma-1)(n-1)^2}{2n(\gamma Ma_e)^2+2\gamma(n-1)}}$	$P_n = P_\infty$

Based on the "virtual nozzle" model, Li et al. [35] developed the two-layer model, which improved the accuracy of the virtual nozzle model in the near-field simulation while ensuring computational efficiency. Hu [36] improved the two-layer virtual nozzle model to make it suitable for impinging jets on a flat plate.

3.3. Experimental research

A) Subsonic jet

Without the influence of wind or obstacles, the leakage of hydrogen into the surrounding space belongs to the research category of free jets. Generally, the outlet velocity of hydrogen leakage is high and the Reynolds number of gas flow is large, which makes the hydrogen leakage belong to turbulent jet. The study objects of early turbulent jet experiments include air and water [37], and experimental studies focused on gas fuel jets have emerged subsequently in large numbers. These experiments were mainly subsonic jet experiments with airflow pressure ratios less than the critical pressure ratio [38-41].

These early experimental studies on methane and other gases provided important references for hydrogen leakage research in terms of experimental technical means, data processing methods, and gas flow parameters. The experimental study of subsonic hydrogen leakage is similar to that of other gaseous fuels. It mainly measures the concentration, velocity, and turbulence characteristics of hydrogen jets. Some of these experiments used ignition tests to obtain hydrogen flammable range and other properties. Schefer et al. [20] used the PLRS experimental system to measure the concentration fields of the jet generated by the leakage of hydrogen and methane gas from a slender leakage pipe with a diameter of 1.91 mm into the air. This experiment used relatively high Froude numbers and found that the attenuation law of the mole fraction of hydrogen and methane along the centerline of the jet is completely consistent, which shows that the self-preservation behavior of the jet axial concentration decay is independent of the type of gas and the outlet velocity. Besides, Schefer et al. [42] studied the influence of buoyancy on jet concentration distribution by using hydrogen gas flow with relatively small Froude numbers, measured the jet velocity field by Particle Image Velocimetry (PIV), and found different characteristics of gas flow parameters at different distances from the leakage outlet. As shown in **Figure 3**.

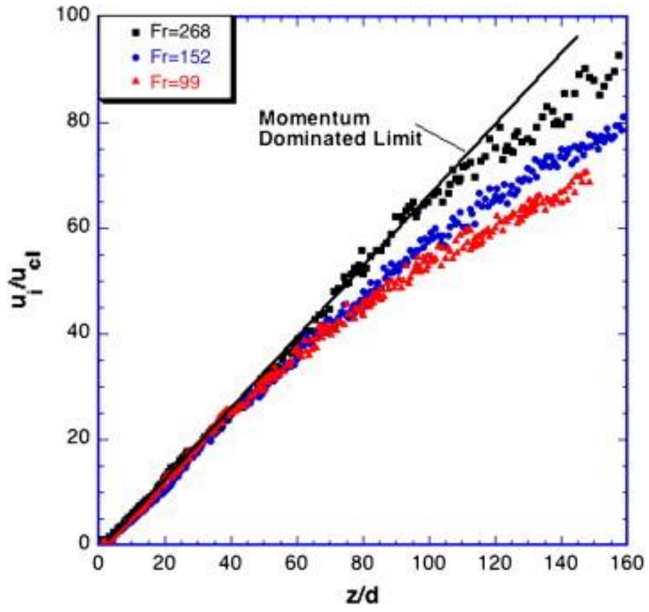

Figure 3. Centerline variation of inverse time-averaged axial velocity in turbulent nonreacting H2 jets. Fr = 268, Re = 2,384 (■); Fr = 152, Re = 1353 (●); Fr = 99, Re = 884 (▴) [42]

In order to obtain the maximum flammable range of low-pressure hydrogen after leakage, some researchers also used the method of ignition at different positions in the jet area to conduct experiments, such as Swain's [43] Arc ignition experiment and Schefer's ignition experiment using Nd:YAG laser pulses with an energy of 1 J.

B) High-pressure under-expanded jet

The experimental research of high-pressure underexpanded gas jets mainly focuses on the visualization of shock structure and the measurement of gas flow parameters such as jet concentration, velocity, and temperature. The experimental technologies and methods include PLRS technology, concentration sensor measurement method, fixed-point sampling, PIV technology, Schlieren imaging, and thermal imaging.

The high-pressure underexpanded jet expands rapidly outside the outlet and forms a normal shock wave called Mach disk, the classical shock wave structure of a high-pressure under-expanded jet is shown in **Figure 4**. At present, the research on Mach disk mostly involves the position of Mach disk from the leakage port, the diameter, thickness, and the curvature of Mach disk [44-46]. Research on the shock wave structure of high-pressure under-expanded jets can be traced back to early aerodynamics research. **Table 3** presents the research of some researchers.

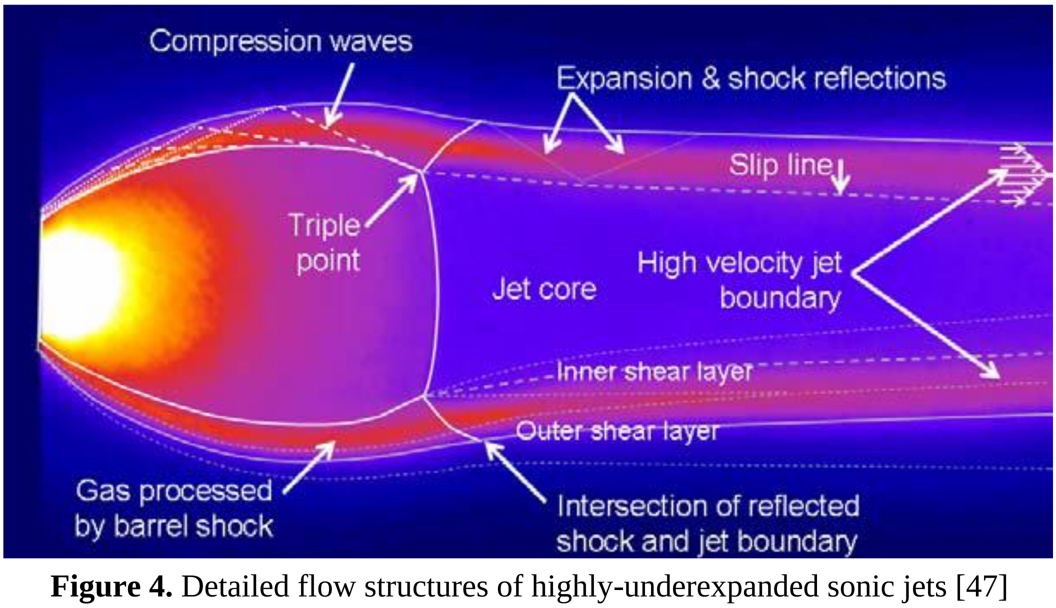

Figure 4. Detailed flow structures of highly-underexpanded sonic jets [47]

Table 3. Some early studies of shock wave structure

researchers	Methods	Experimental gas	Results
Birch et al. [48]	Schlieren imaging	High-pressure supersonic natural gas jet	Measured the concentration of natural gas along the axis and concluded the regularity of self-similar.
Crist et al. [49]	Schlieren imaging hot-shot wind tunnels	Nitrogen, Norgon, Helium, helium-argon mixture, CO2, etc.	Received empirical formula of the diameter.
Ewan, Moodie [50]	Shadowgraphy Laser Doppler Velocimetry	High-pressure supersonic air jet	Measured the speed of jet along the axis and concluded the regularity of similarity of speed decline along the axis.
Addy et al. [51]	Schlieren imaging	High-pressure supersonic air jet	Concluded the influence of different shapes of nozzle on the location and size of Mach Dick.

Based on the above-mentioned research on various jet forms, especially in this century, researchers have conducted extensive research on high-pressure hydrogen gas [52-55]. A typical example is a series of hydrogen jet visualization experiments under different working conditions conducted by the Sandia National Laboratory in the United States, including the measurement of the shock wave structure of the high-pressure hydrogen jet by schlieren imaging and the concentration field of the hydrogen jet by laser Rayleigh scattering technology [20,56-59]. Among them, Ruggles and Ekoto [57] observed a shock wave structure similar to that of Brich's [48] experiment, Schefer et al. [59] established the first theoretical model that can be used to calculate high-pressure hydrogen under-expanded jets. Subsequently, Molkov et al. [60] and Yuceil et al. [61] improved the prediction model.

Because of the high natural dangerousness of hydrogen experiments and the limitation of the measurable parameter, helium is generally used to replace hydrogen for high-pressure under-expansion jet experiments to reduce risks, but it will also increase costs. With the continuous improvement of modern computer performance, computational fluid dynamics (CFD) technology is widely used in the simulation research of high-pressure hydrogen jets under different working conditions. The use of large eddy simulation (LES) [62], detached-eddy simulation (DES) [63], and adaptive grid technology [64] to simulate high-pressure hydrogen jets has become the study hot in academia.

4. Fault Diagnosis

The reliability of the system can be improved through fault diagnosis. At present, the application of fault diagnosis technology has existed in many fields, and it can detect the fault of the system and parts [65]. Common fault diagnosis methods are shown in **Figure 5**. Mechanism model method and signal processing method are commonly used traditional fault diagnosis methods. However, due to the increased complexity in the structure of the equipment and the influence of various interference factors, it is not easy to be applied under certain conditions. On the other hand, artificial intelligence has been improved rapidly, which has certain advantages compared with traditional fault diagnosis methods. Therefore, the artificial intelligence method is also deeply researched and widely applied [66]. In addition, the use of a single fault diagnosis method has its limitations, so a mixed diagnosis method can be used when performing fault diagnosis on a complex system [65].

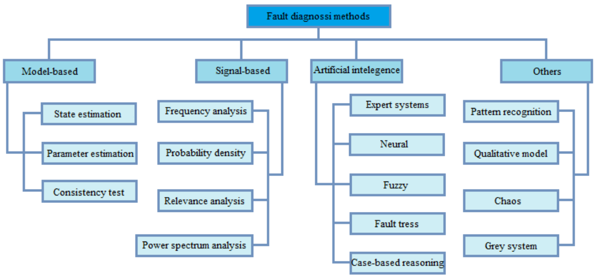

Figure 5. Classification chart of common fault diagnosis methods [67-70]

In recent years, the application of hydrogen fuel cells has been gradually extended to the civilian field, and hydrogen leakage is very necessary to be diagnosed in time. At present, preliminary studies have been conducted on the causes, classification, and diagnosis methods of hydrogen fuel cells in China and abroad. In foreign countries, the main method is to detect various parameters in the system and establish model analysis to analyze various faults in the hydrogen fuel cell [71-73]. Research in China on fault detection and control systems is mainly from the perspective of industrial manufacturing by Wuhan University of Technology [74-77]. However, the research on the fault diagnosis of hydrogen fuel cells still needs to be in-depth, and problems such as relatively simple research objects, incomplete analysis, and low accuracy still remain [65].

5. Gap and Future perspectives

A) Mach disk

The research on the shock wave structure in the high-pressure under-expanded hydrogen jet only focused on the position of the Mach disk. There are empirical formulas with high accuracy [78]. However, the measurement results of the diameter of the Mach disk are few, and the empirical formula can only be used under limited conditions [79]. And there is almost no measurement data on the thickness of the boundary layer around the Mach disk. The relationship between the dimensionless diameter of the Mach disk and the square root of the jet pressure ratio is not a simple linear relationship. It is difficult to accurately express the Mach disk diameter formula by using the jet pressure ratio.

B) Leakage of cryogenic compressed hydrogen

Although the solution to high-pressure hydrogen leakage has developed in recent years, for fuel cell vehicles, there are few studies on low-temperature hydrogen at present, especially low-temperature compressed hydrogen, and a small number of experimental measurement studies are limited by the lack of measurement methods and data processing technologies. The experimental data of studies are often very rough, and it is difficult to conduct a more in-depth analysis. And in some existing experiments, the laser Raman scattering signal intensity is weak, which is susceptible to the interference of background stray light, so the acquired experimental data contains a lot of numerical noise [80]. In 1998, LLNL proposed the concept of low-temperature compressed hydrogen (80K, 248bar), and began to explore the use of insulated high-pressure vessels for hydrogen storage in vehicles [81] and reported the use of the insulated high-pressure vessels in Ford and Toyota in 2010 [82]. In the past ten years, low-temperature compressed hydrogen has received more attention from researchers as a hydrogen storage method that combines the advantages of low temperature and high pressure [83-88]. It is predictable that due to the need for quantitative risk assessment and related standards and specifications updates, there will be more and more researches on cryogenic compressed hydrogen leaking jets.

C) Geometry changes of leak holes

The existing "virtual nozzle model" and "two-layer" models greatly facilitate the study of hydrogen jets from circular nozzles, but they lack corresponding solutions for leaking jets from narrow and long nozzles that are closer to the real situation. Therefore, in the field of hydrogen safety risk assessment, hydrogen leakage is usually simply simplified as a circular nozzle jet. Due to the huge difference between circular nozzles and special-shaped nozzles, some safety hazards is likely to be caused by this simplification method. The geometry of the leakage port will significantly affect the flow and diffusion of the jet. For example, the change in the cross-sectional area of the leakage port in the flow direction and the degree of deviation of the cross-section from the circle may change the diffusion rate of the jet [89,90]. In order to solve the problem that the leakage port is not circular in practical problems, the circularly symmetric nozzles are usually assumed to be elliptical or rectangular, but there are little researches on special-shaped nozzles, especially rectangular nozzles. There are only a few studies on the qualitative research on the jet diffusion of rectangular nozzles, without considering the effect of the aspect ratio change on the jet [91], and the discharge pressure of the concentration diffusion study is low. So the research of concentration field measurement of the high-pressure discharge is lacking. In addition, the accuracy of the turbulent models commonly used in numerical simulation research applied to the jet flow of rectangular nozzles, such as the k-ε model, still needs to be verified.

In addition to the geometry of the leak, when describing and analyzing the flow field characteristics and influencing factors of the hydrogen leakage and diffusion of the hydrogen storage container, the stability of the wall crack of the hydrogen storage container determines the change of the leakage aperture size during the leakage and diffusion of the hydrogen. The diffusion flow field is also influenced by it. Under the damage conditions of hydrogen storage pressure vessels, crack propagation and leakage interact brings a lot of potential dangers to the safety of the vessel, but there is no clear theoretical model for this kind of problem. In the future, it is necessary to analyze through the mechanical analysis of the crack, combined with the cross-subjects related to hydrogen damage, and summarize the theoretical methods for analyzing the stable state of the crack.

D) Numerical simulation research

At present, CFD technology is widely used in the simulation study of high-pressure hydrogen jets under different working conditions. The difficulty of CFD simulation of subsonic hydrogen leakage is relatively low, and the requirements for the performance of the calculation grid are not very high. But challenges are still present in simulating high-pressure hydrogen jets. The accuracy of CFD simulation is often affected by some constants in the model, such as the turbulent Schmidt number. The choice of these constants often has a great influence on the calculation results [30], and may even affect the low-pressure leakage simulation [92]. In addition, the accuracy of CFD simulations can be influenced by the choice of turbulent models [86,87]. As a result of the fierce change of gas flow parameters and shock wave structure outside the leakage point of the high-pressure under-expanded hydrogen jet, the numerical calculation is difficult to stabilize and converge [93]. For an accurate calculation, a very fine grid must be arranged near the leakage point; on the other hand, it is necessary to set a small Courant number in the calculation to ensure that the calculation does not diverge. The time cost of CFD calculation will be dramatically increased by these problems, so some high-pressure jet simulation experiments only simulate the flow in the area close to the leakage outlet [94,95].

Due to the computational cost of CFD, the virtual nozzle model, which simplifies the simulation, has become a substitute, but it ignores the air drawn into the jet, the uncertainty of the temperature [95], and the airflow actually only partially passes through the Mach disk [96]. It is impossible to simulate the actual flow zone situation, and the calculation result is not accurate enough. At present, more modeling work is needed to improve the current simplified simulation method, and more experimental data under high pressure is needed to verify the corresponding CFD model. In addition, the virtual nozzle model is not capable to simulate some flow partition conditions, so a new model needs to be established to consider the jet core flow area and boundary layer area at the same time.

6. Conclusion

Nowadays, the utilization of hydrogen as an alternative fuel has gained considerable attention. The hydrogen energy industry, represented by hydrogen fuel cell vehicles, will develop rapidly and high-pressure hydrogen storage technology is relatively mature. However, once the hydrogen storage equipment is damaged, a large amount of hydrogen will be quickly released into the surrounding environment which is likely to cause combustion or explosion accidents. Based on the above background, the following questions are taken into consideration.

A variety of hydrogen production schemes under different conditions are discussed. The production of hydrogen from methane gas will produce carbon dioxide, and the technology of water electrolysis could lead to excessive energy consumption. The most ideal method should be hydrogen production from renewable energy sources such as solar energy and biological energy, which have obvious environmental benefits and cost advantages if the technology is developed. The shortcomings of high-pressure storage, the current theoretical research results of high-pressure hydrogen leakage, and the development status of various relevant theories are analyzed in detail. The article concluded that there is a lack of research on low-temperature compressed hydrogen leakage and special-shaped nozzle leakage. There are many simplified model methods for the study of high-pressure under-expanded hydrogen jets, and more accurate and widely applicable research should be conducted in the future.

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