STUDY OF FIRE RISK AND ACCIDENTS EMEREGENCY DISPOSAL TECHNOLOGY SYSTEM OF HYDROGEN FUEL VEHICLES

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ABSTRACT

As the energy crisis and environment pollution growing severely, the hydrogen fuel motor vehicle has got more and more attention, many automobile companies and research institutions invest significant R&D resources to research and develop the hydrogen fuel vehicles. With the development of the hydrogen fuel cell vehicles and hydrogen fuel motor vehicles, the hydrogen had more to more extensive application. According to the categories of the hydrogen fuel vehicles, the characteristics of hydrogen fuel vehicle fire risk and accidents are analyzed in this paper. As for hydrogen fuel cell vehicles, the function of its key components such as the fuel cell, the high-pressure storage tank is presented firstly. Then, based on the low density, fast diffusion and flammable of hydrogen, the probable scenarios of accident such as fuel leak, jet flame are analyzed and the fire risk of the key components and the whole vehicle is evaluated. Finally, the development trend of the emergency warning system of hydrogen fuel cell vehicles is analyzed and some recommendations are proposed referring to the detection, pre-warning and control technologies used in the industrial sites. Aiming at the hydrogen car structure characteristics and the fire accident modes and accidents evolution rules, the emergency disposal technology system for hydrogen fuel motor vehicles is put forward.

Keywords: fire risk, emergency disposal technology, hydrogen fuel

1.0 INTRODUCTION

As the traditional energy like petroleum, coal exhausted and the environmental problems became serious, all countries in the world began to explore implement the diversification of energy, and research the new energy. As a clean energy, hydrogen has got more and more attention due to its characteristics of wide availability, highly environmental protection, renewable ability and so on. Meanwhile, with the increasing number of vehicles in the world, the transportation energy consumption has become one of the main sources of the environmental pollution. Thus, many automobile manufacturers and research institutions pay their attentions on the hydrogen fuel vehicles and invest significant R&D resources to research this kind of vehicles[1]. Until now, there are two kinds of hydrogen fuel vehicles in the world, called hydrogen fuel cell vehicles and hydrogen fuel motor vehicles. The research on the hydrogen fuel motor vehicles started earlier. Ricardo and Burstoll studied the hydrogen internal-combustion engine firstly in the early twentieth century, and the Tokyo City University and NISSAN developed a liquid hydrogen vehicle called “Musashi” in 1990. Then, a number of automobile manufacturers in the world such as Ford, BMW launched their hydrogen fuel motor vehicles one after another, and the research of fuel motor vehicles entered a new epoch. Based on it, the European Commission initiated and promoted an optimized hydrogen internal-combustion engine in 2007, and the reliability of this engine is subsequently confirmed in the fuel motor car and bus. However, the development of hydrogen fuel cell vehicles was relatively slow. Though Sir Grove discovered the theory of the fuel cell in 1839, the application had not been developed because the hydrogen could not be obtained from natural environment directly. It is not until the 1960s that General Motors (GM) produced the first hydrogen fuel cell vehicle in the world. Then the hydrogen fuel cell vehicle got the unprecedented development in 1990s, and the major automobile manufactures invested a lot of manpower and resources to research and develop it. At present, Japan is in the forefront of the world in the field of hydrogen fuel cell vehicles. Toyota developed a hydrogen fuel cell vehicle called ‘MIRAI’, and looked forward to achieve a sales goal of 30 thousand vehicles by 2020. Honda also launched their hydrogen fuel cell vehicle called ‘Clarity’ in 2016. Furthermore, China is actively developing the hydrogen fuel cell vehicle at present, and has developed the 'beyond' series of hydrogen fuel cell cars and two types of fuel cell buses. Meanwhile, the demonstration project of hydrogen fuel cell vehicles has launched in Beijing Olympic Games and Shanghai World Expo.

At present, although hydrogen fuel vehicles, especially fuel cell vehicles are developing rapidly, there are still many key problems left to be solved, such as the high cost of the proton exchange membrane. Furthermore, the hydrogen fuel vehicle is also facing the threats from fire and explosion hazards. Due to the wide range of explosion limits, the low ignition energy and the fast combustion speed of hydrogen, the disaster degree of hydrogen fuel vehicles is larger than the traditional vehicles. Thus it is important to analyze the fire and explosion risk of hydrogen fuel vehicles and to evaluate the reliability and safety. However, there are few studies on the fire and explosion risk analysis of hydrogen fuel vehicles, and only some of the researchers have paid their attention on these issues. choi et al.[2] observed the fire behavior of actual fuel cell vehicle, comparing with that of gasoline vehicle. Watanabe et al.[3] proposed a new comprehensive facility for the evaluation of hydrogen and fuel cell vehicle safety. The facility could also be used to establish the international regulations, codes and standards. Vudumu[4] conducted numerical simulation to investigate the behavior of hydrogen mixing and associated flammability limits in air during an accidental release, and the safety risks of hydrogen fuel vehicles were evaluated.

The studies mentioned above show that the risk analysis of hydrogen fuel vehicles considering all the probable accident modes is still lacking, and the study on the emergency disposal technology for hydrogen fuel vehicles is especially in shortage. In this paper, according to the categories of the hydrogen fuel vehicles, the function of their key components is presented and the probable accident modes are studied. Then, the fire and explosion risk of different accidents modes is analyzed. Based on it, the emergency disposal technology system for hydrogen fuel vehicles is put forward.

2.0 CATEGORY AND FUNCTION

As mentioned above, the hydrogen fuel vehicle is mainly divided into two kinds: hydrogen fuel motor vehicles and hydrogen fuel cell vehicles. The former uses the hydrogen internal-combustion engine reformed from the traditional engine, and the latter uses the power system driven by the fuel cell. Compared with the traditional vehicle, the main difference of the hydrogen fuel vehicle is the existence of the hydrogen supply system, fuel cell stack (fuel cell vehicle), and hydrogen internal-combustion engine (fuel motor vehicle).

At present, the widely used on-board hydrogen supply system consists of high- pressure storage tank, solenoid valve, pressure reducer and so on. The design pressure of the storage tank is 70MPa, and the weight percentage is 5.7wt%. The high-pressure storage tank usually has three layer structures, among which thermoplastic carbon fiber-reinforced plastic is the most important layer making the storage tank high strength, anti-permeability, anti-bump.

Fuel cell is an electrochemical device that converts the chemical energy into electric energy. The fuel cell stack consists of the proton exchange membrane, catalyst layer, gas diffusion electrode and so on. The hydrogen is fed to the anode while oxygen is fed to the cathode. The electric energy is generated by the electrochemical oxidation of hydrogen, and the electrochemical reduction of oxygen. The reactions take place to produce an electric current, and water becomes the only waste in the reaction. The schematic of the fuel cell is shown in Fig.1. As long as the hydrogen and oxygen are continuously supplied to the electrodes, the fuel cell has the capability to produce electric energy. Besides the fuel cell stack, the on-board fuel cell system requires other components, such as fuel processor, power conditioner, and so on. The integrated system provides the power to drive vehicles.

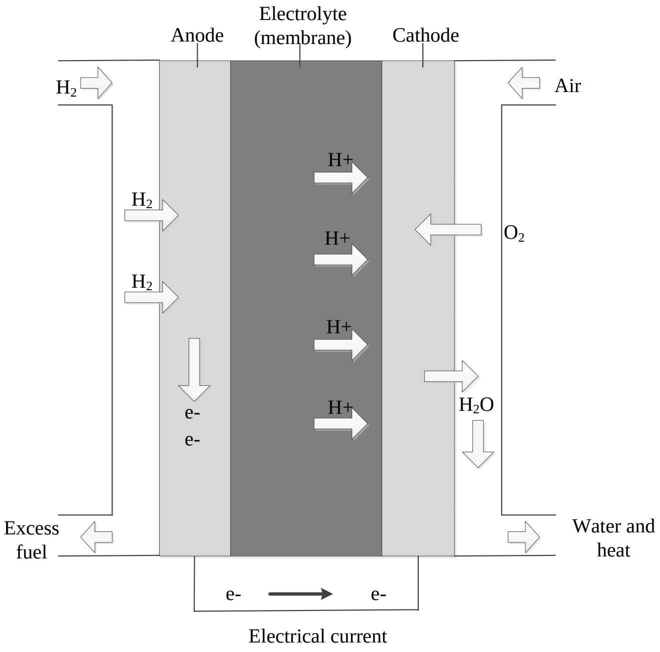

Figure 1. Schematic of a fuel cell

According to the different positions injecting the hydrogen fuel, the hydrogen internal-combustion engine can be divided into two types: cylinder-injection and in-cylinder direct-injection. The structure of the cylinder-injection is simple, which is similar to the traditional internal-combustion engine, and as a result it is most widely used in the hydrogen fuel motor vehicle. However, this kind of engine needs to occupy large amount of cylinder space, which limits the development of this engine. Compared with cylinder-injection, the in-cylinder direct-injection engine does not occupy the cylinder volume, which can increase the engine power greatly. But this engine has not been used widely because some key problems have not been solved.

3.0 RISK ANALYSIS OF HYDROGEN FUEL VEHICLES

According to the introduction about the key components of hydrogen fuel vehicles, the probable safety issues will be analyzed and the accident scenarios and modes will be identified in the following sections. Based on it, the fire and explosion risk of hydrogen fuel vehicles will be evaluated.

3.1 Identification of Accident Modes

Hydrogen has the characteristics of low density, fast diffusion and highly inflammability, while the fire risk is class A. Thus, once the leak appears in the process of storage, supply, and filling, the fire and explosion accidents may happen. The reason for leakage of hydrogen fuel vehicles is various, for example, hydrogen may penetrate into the carbon of metal equipment, which leads to the hydrogen embrittlement failure of storage tanks and transportation pipelines. As a result, the leakage of hydrogen will happen. The crash accident of vehicles may also lead to the leakage of hydrogen. Furthermore, when the tank is filled with hydrogen under pressure, the incorrect operation may cause the hydrogen leak.

For hydrogen supply system, in the event of a hydrogen leak as a result of a crash or corrosion, the hydrogen will vent out from tanks or pipelines. The ejections of a hydrogen fluid give rise to a jet flame if the fluid ignites (Scenario 1). Furthermore, if the hydrogen storage tank is exposed to a fire or a jet flame, the internal pressure of the tank will increase as a result of heating. Under normal circumstances, the thermal pressure relief device (TPRD) installed on the storage tank will be activated when the temperature of the tank reaches the critical value, followed by the release of hydrogen gas though TPRD. This ejection close to an ignition source will also cause a jet flame (Scenario 1). However, if TPRD fails as a result of crash, shock for example, the high-pressure hydrogen cannot be released. As the temperature of the storage tank rises, the internal pressure will increase and the strength of the tank will continue to decrease. Eventually the storage tank will be subjected to a BLEVE (Scenario 2). BLEVE is a serious disaster, which will result in large-scaled human casualties.

The crash accident of vehicles may result in the leakage of hydrogen and oxygen from the hydrogen internal-combustion engine. This leakage will form the combustible hydrogen-air mixture in the engine compartment. Once the mixture reaches explosion limit, an explosion may occur if the ignition sources exist nearby (Scenario 3-1). Moreover, Hydrogen-air mixture may leak to the passenger compartment in some special conditions, and give rise to an explosion (Scenario 3-2). It is worth mentioning that a serious crash accident could also cause a hydrogen leak from tanks and pipelines. If the leak occurs in a relatively confined space, the likelihood of explosion is very high. Furthermore, when hydrogen fuel is filling to hydrogen fuel vehicles, a hydrogen leak may occur due to incorrect operation or non-respect of the instructions. If the leak is contained in a close compartment and an ignition source exists nearby, an explosion could occur and lead to a catastrophic result (Scenario 3-3). It can be summarized that the explosion scenario of hydrogen fuel vehicles is divided into two kinds: an explosion in engine/passenger compartment and an explosion in hydrogen supply environment.

For hydrogen fuel cell vehicles, because the service life of the proton exchange membrane is relatively short, typically of a few hundreds or thousands of hours, the electrolyte failure is a frequent event. This failure will result in the mixture of hydrogen and oxygen leading to risks of internal combustion (Scenario 4).

Based on the analysis mentioned above, the accident modes and evolution rules of hydrogen fuel vehicles is given in Fig.2 by using classical fault tree representations. Though the frame of Fig.2, one can identify the accident modes of hydrogen fuel vehicles more clearly. It is noted that this paper does not discuss the accident modes that the traditional vehicles could also occur, such as fire caused by circuit short, arson and so on.

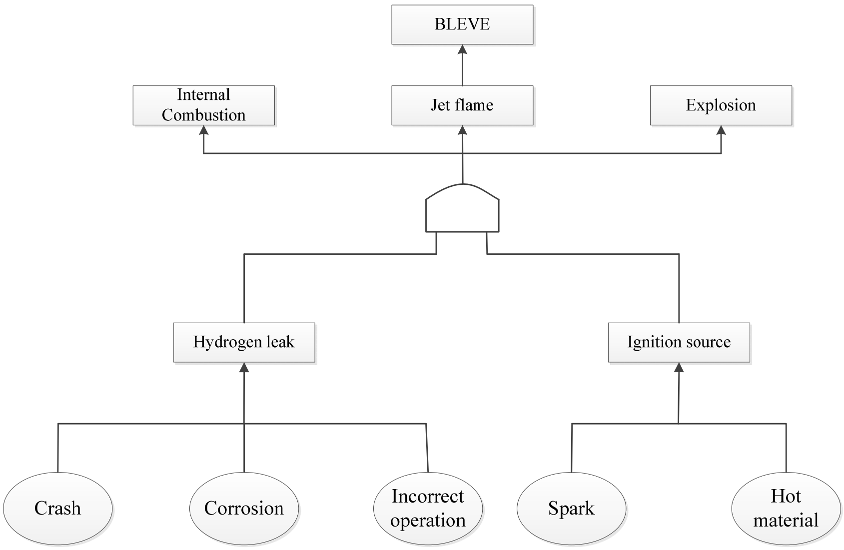

Figure 2. Accident evolution rules of hydrogen fuel vehicles

3.2 Risk Analysis of Accidents

In this section, the risk of above accidents will be evaluated using TNT equivalent method and radiation intensity model of jet flame. Both approaches allow us to quantify the effects of different accidents on the people.

3.2.1 TNT equivalent method

TNT equivalent method is usually used to calculate the damage radius of an explosion, and divide the dangerous area[5]. Concerning the explosion of hydrogen fuel vehicles, the TNT equivalent method is used to obtain the explosion risks. The explosion energy of hydrogen fuel vehicles is equivalent to TNT weights, the expression can be given as:

$$W_{TNT} = \frac{AW_h Q_h}{Q_{TNT}} \ , \tag{1}$$

where A – equivalent weight factor of TNT, A=0.02%-14.9%; W_f – weight of hydrogen, kg; Q_f – combustion heat of hydrogen, MJ/kg; Q_TNT – heat of detonation of TNT, Q=4.12 MJ/kg.

According to the TNT weight calculated by Eqs.(1), the explosion risk of hydrogen fuel vehicles can be evaluated by the factor called scaled distance, which is always used in the calculation of peak overpressure and impulse of TNT explosion. The equation to calculate the scaled distance is shown in Eqs. (2):

$$R = \frac{Z}{W_{TNT}^{1/3}} \ , \tag{2}$$

where R – scaled distance, m/kg$^{1/3}$; Z – distance from the centre of the explosion, m; W_TNT – TNT equivalent weight of the explosive gas, kg.

Based on the diagrams given by UFC[6] and widely used formula proposed by Henrych[7], as shown in Eqs.(3), the explosion overpressures at different distances from hydrogen fuel vehicles can be determined versus scaled distances. NATO[8] specification in U.S points out that the pressure threshold causing 2% probability of eardrum rupture is about 20kPa, the pressure threshold causing the injury of human lung is about 34.5kPa, and the pressure threshold causing 1% probability of human death is about 103.4kPa. Based on the different thresholds, three damage degrees can be determined： minor injury, serious injury and death. Thus, the damage radius corresponding to different damage degrees can be identified using calculation methods mentioned above.

$$\begin{aligned}
\Delta P_f &= \frac{1407.17}{R} + \frac{553.97}{R^2} - \frac{35.72}{R^3} + \frac{0.625}{R^4}, 0.05 \le R < 0.3 \\
\Delta P_f &= \frac{619.38}{R} - \frac{32.62}{R^2} + \frac{213.24}{R^3}, 0.3 \le R < 1 \qquad , \\
\Delta P_f &= \frac{66.2}{R} + \frac{405}{R^2} + \frac{328.8}{R^3}, 1 \le \mathrm{R} \le 10
\end{aligned} \tag{3}$$

3.2.2 Radiation intensity model of jet flame

The jet flame of hydrogen fuel vehicles caused by the leakage of hydrogen damages the surrounding people by the thermal radiation. This radiation can be calculated by radiation intensity model of jet flame. It is assumed that the entire jet flame is composed of all the point heat sources along the jet centerline, and the radiant heat flux of each point heat source is the same. The expression for calculation of radiant heat fluxes is given as:

$$q = \eta v Q_h \ , \tag{4}$$

where q – radiant heat flux of the point heat source, kW; η – efficiency factor; v – leakage rate of hydrogen, kg/s; and Q_h – combustion heat of hydrogen, MJ/kg.

As Eqs.(4) shows that the leakage rate of hydrogen is an unknown quantity, its value is related to the flow speed and the pressure in the tank. According to Bernoulli equation and Poisson adiabatic equation, the leakage rate can be estimated by Eqs. (5):

$$v = YC_d AP\sqrt{\frac{Mk}{RT}\left(\frac{2}{k+1}\right)^{(\mathrm{k}+1)/(\mathrm{k}-1)}} \ , \tag{5}$$

when $\frac{P_0}{P} \le \left(\frac{2}{k+1}\right)^{k/k-1}$, the gas flow belongs to sonic flow, the flow factor Y=1.0;

when $\frac{P_0}{P} > \left(\frac{2}{k+1}\right)^{k/k-1}$, the gas flow belongs to subsonic flow，the flow factor Y can be calculated by Eqs. (6):

$$Y = \left(\frac{P_0}{P}\right)^{1/\mathrm{k}} \times \left(1 - \left(\frac{P_0}{P}\right)^{(\mathrm{k}-1)\mathrm{k}}\right)^{1/2} \times \left(\left(\frac{2}{k-1}\right) \times \left(\frac{k+2}{2}\right)^{(\mathrm{k}+1)/(\mathrm{k}-1)}\right)^{1/2}, \tag{6}$$

where C_d – leak factor of gas; A – area of the gap, m^2; M – molar mass of gas, kg/mol; k – adiabatic index, which is equal to the ratio of constant-pressure specific heat and constant-volume specific heat, for hydrogen k=1.41; R – gas constant, R=8.314J/(mol K); T – temperature of the environment, T=293K; P_0 – atmospheric pressure, MPa; P – hydrogen pressure in the storage tank, P=70MPa.

Once the radiant heat flux of the point heat source is determined, the incident radiation intensity of the target (Z meter from the point) can be calculated by the following equation.

$$I = \frac{q\lambda}{4\pi Z^2}, \tag{7}$$

where, I – radiation intensity, kW/m^2; q – radiant heat flux of the point heat source, kW; λ –radiant energy fraction.

When the radiation intensity of jet flame is strong enough, the surrounding people and equipment could be damaged. Table 1 gives the damage corresponding to different radiation intensities. Based on the different damage thresholds shown in Table 1 and Eqs.(7), the different damage radiuses will be determined.

Table 1. Damage conditions corresponding to different radiation intensities

Damage area	Radiation intensity(kW/m2)	Injury to people
Death area	I⩾37.5	1% probability of death(10s), 100% probability of death(1min)
Serious injury area	25⩽I＜37.5	Extensive burn(10s) , 100% probability of death(1min)

Damage area	Radiation intensity(kW/m2)	Injury to people
Minor injury area	12.5⩽I＜25	First-degree burn(10s), 1% probability of death(1min)
Dangerous area	4⩽I＜12.5	Feeling pain (>20s)

3.2.3 Case study

Based on the calculation model for explosion and jet flame, the risk analysis will be carried out in this section using hydrogen fuel cell car and upcoming bus produced by Toyota as the subjects. The hydrogen fuel cell car ‘MIRIA’ has two high-pressure hydrogen storage tanks with a total volume of 122.4L and a weight of 5kg approximately. The volume of the passenger compartment is about 3.5m^3, while the volume of the fuel cell stack is 37L. Concerning the probable accident modes such as jet flame, explosion and BLEVE, the damage radius corresponding to different accident modes is determined, as shown in Table 2. Fuel cell bus has ten high-pressure hydrogen storage tanks with a total volume of 600L and a weight of 25kg. The volume of the passenger compartment is about 60m^3, and the volume of the fuel cell stack is 74L. The probable accident modes are nearly the same with the hydrogen fuel cell car, but the positions where the accidents occur may be different. Considering the real scenarios, the damage radius of fuel cell bus corresponding to different accident modes is identified, as shown in Table 2.

It can be seen from the table that no matter what the accident mode is, the damage degree of fuel cell bus is larger than fuel cell car due to the larger volume and more hydrogen storage tanks. For both fuel cell car and bus, BLEVE (S2) is the most serious accident mode. Compared with BLEVE, the severity of explosion in passenger compartments (S3-2) is relatively low, while the severity of explosion in fuel cell stacks (S4) remains rather limited because the internal combustion occurs inside the gas channel of the stack. Furthermore, the damage degree of the jet flame (S1) is similar to the explosion in passenger compartments. It is worth mentioning that compared with the leakage in the passenger compartment, the amount of hydrogen may be greater at a filling station, if the supply is not stopped by artificial or automatic cutoff. Thus, the consequences of this kind of explosion (S3-3) are catastrophic. Due to the uncertainty, the damage degree of this event is between BLEVE and jet flame as a simplification. Moreover, it is also assumed that the damage degree of the explosion in the engine compartment of hydrogen fuel motor vehicles (S3-1) is the same as the explosion in fuel cell stacks.

Table 2. The calculation results of different accident modes

Accident mode	Vehicle type	Death radius/m	Serious injury radius/m	Minor injury radius/m
BLEVE (S2)	Fuel cell car	7.28	13.33	18.56
	Fuel cell bus	12.44	22.79	31.75
Explosion (S3-2)	Fuel cell car	1.93	3.54	4.93
	Fuel cell bus	4.98	9.12	12.70
Explosion (S4)	Fuel cell car	0.42	0.78	1.08
	Fuel cell bus	0.53	0.98	1.36
Jet flame (S1)	Fuel cell car	1.51	4.39	6.83
	Fuel cell bus	3.34	9.73	15.12

Besides the severity of accident modes, the frequency of each accident mode should also be considered in the risk analysis. BELVE (S2) and catastrophic explosion (S3-3) are almost improbable events, the frequency of these events is estimated about to 10^{-6} events per year[9]. The frequency of a serous leakage is about 10^{-5} events per year, which is regarded as the same with the failure of the internal-combustion engine (S3-1). Furthermore, the internal combustion of fuel cell stack (S4) is a frequent event due to the low service life of the electrolyte. The frequency of this event is larger than 10^{-1} events per year.

Based on the severity and probability analysis of accident modes mentioned above, each accident mode is distributed in the grid, as shown in Fig.3, and the level of the risk for each mode is determined. It can be seen from the figure that the accident modes of S1, S2, S3-2, S3-3 and S4 should be mainly focused for prevention and disposition.

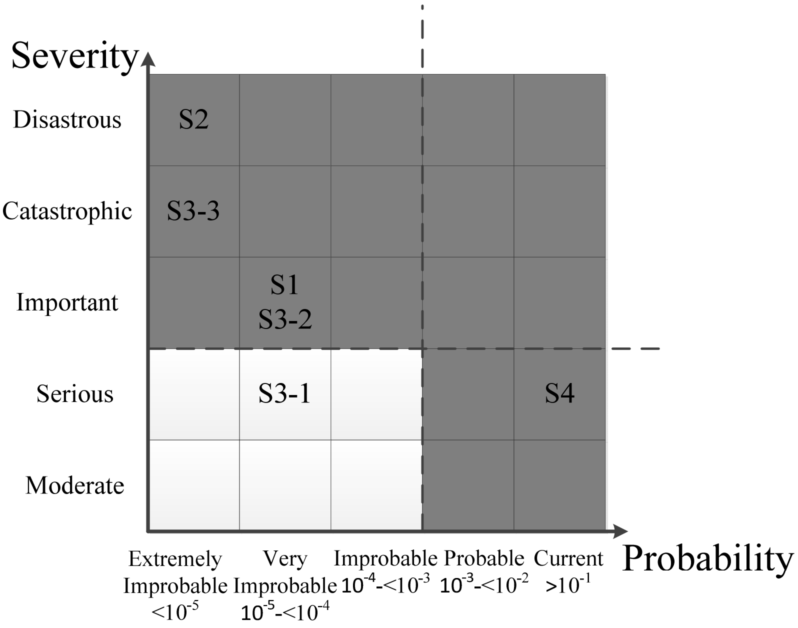

Figure 3. The sketch of severity and probability of accident modes

4.0 EMERGENCY DISPOAL THECHNOLOGY SYSTEM

Aiming at the hydrogen fuel vehicle characteristics, the accident modes and accidents evolution rules, the emergency disposal thechnology system should be put forward to prevent and control the accidents of hydrogen fuel vehicles. This system includes two parts: intrinsically safe of hydrogen fuel vehicles and emergency disposal measures in the scene of the accident. For the hydrogen supply system, all the storage tanks, pipelines and valves must be suitable for hydrogen, and have sufficient safety margin to withstand the pressure. The hydrogen supply system should be examined several times to ensure the air tightness. A overcurrent protection device should be installed on the outlet of the hydrogen storage tank, once the leakage occurs and the gas flow is larger than 1.2 times maximum flow, the protection device will be activated to cut the feeding. Moreover, a hydrogen leak monitoring system should be installed near the storage tanks, passenger compartment and fuel cell stack. When any sensor detects the hydrogen concentration exceeding 10, 30, 50 percent of the low explosion limit, the monitoring system will send out different levels of sound and light signals, and at the same time, the solenoid valve is activated to cut off hydrogen supply. The most important component in this system is the hydrogen sensor. At present, there are lots of hydrogen sensors used in the industrial sites and fuel vehicles. However, these sensors have their inherent problems, such as short service life, low sensitivity and so on. With the development of the graphene, a Pt-Pd/reduced graphene oxide based sensor has been proposed. In order to detect the hydrogen leak better, this sensor could be used in hydrogen fuel vehicles due to its high sensitivity, short response time, good stability and low cost. Furthermore, grounded leads should be set at the bottom of the hydrogen fuel vehicle to prevent fire and explosion resulting from the electrostatic accumulation.

In the event of a hydrogen leak as a result of crash, corrosion or incorrect operation for example, the required disposal procedure taken by fire fighters includes investigation-procuratorate, vigilance, protection, disposal action, washing-disinfection, and site recovery. Aiming at different accident modes, the disposal actions are described below. When the leakage of hydrogen occurs, the effective disposal measure is to eliminate all ignition sources nearby, and to let hydrogen quickly dissipate into the atmosphere, while the fire fighters plugging the leak site. But once the hydrogen ignites, a jet flame (S1) or fire may develop. Under this condition, the heat detector should identify flames and give a signal to solenoid valves to cut off hydrogen supply. Meanwhile, the fire fighters should use high-pressure water gun facing the ejection direction to extinguish the flame. To limit BLEVE (S2), the cooling water should also be sprayed to hydrogen storage tanks to reduce the temperature and maintain the strength. Furthermore, the TPRDs installed on storage tanks should have sufficient reliability to ensure the hydrogen release from tanks. To prevent the explosion occurred in engine and passenger compartment (S3-1, S3-2), the fire fighters should use water-misting gun to control the hydrogen concentration below the low explosion limit, and make hydrogen-air mixture dissipate safely. In addition to the measures taken by firefights, an active explosion suppression device is suggested to prevent the explosion in the confined spaces. At present, the widely used active suppression technologies in industry are water mist suppression and inert gas suppression. For hydrogen, researchers have found that fine water mist has favourable effects on explosion suppression of the hydrogen-oxygen mixture[10]. Thus, the fine water mist device used in hydrogen fuel vehicles should be developed and set in the engine and passenger compartments. Once the leakage of hydrogen is detected by the sensors mentioned above, the suppression device will spray the fine water mist into the spaces to prevent the explosion or to reduce the consequences of the explosion. To prevent the internal combustion (S4), it is enough to control the cell potential of each membrane electrode that becomes equal to zero in this event and then cut off hydrogen supply. Furthermore, to prevent the explosion accident during the filling process (S3-3), not only the reliability of the filling system should be guaranteed, but also the operation staff should be trained.

5.0 CONCLUSION

With the development of hydrogen fuel vehicles, the safety problems should be paid enough attention. According to the categories of fuel vehicles, this paper introduces the characteristics of fuel cell vehicles and fuel motor vehicles, including hydrogen supply system, fuel cell stack and hydrogen internal-combustion engine. Based on it, the accident modes and accident evolution rules of hydrogen fuel vehicles are proposed and the risk of each accident mode is evaluated. The results show that the main accident modes are jet flame, BLEVE, explosion and internal combustion. Although the frequency of BLEVE and explosion at the filling station is exceptionally low, these events cause the most serious damage. Moreover, the risk of jet flame and explosion in passenger compartments remains critical. The risk of internal combustion in the fuel cell stack appears as the most frequent event, even though the damage degree is relatively slight. Based on the risk analysis, the emergency disposal technology system for hydrogen fuel vehicles is put forward eventually. This system includes the intrinsically safe of hydrogen fuel vehicles, and disposal technology in the scene of the accident. The monitoring system detects the leakage of hydrogen, and then control the solenoid valve to cut off hydrogen supply. The jet flame could be extinguished by water jet, while the storage tank should be cooled to prevent BLEVE. The explosion could be prevented by using water-misting gun. Furthermore, the explosion suppression device is suggested to install in the engine and passenger compartments to prevent explosion. Other important aspects that must be considered are earthing of equipment, installing flame-proof motors, and so on. Based on the analysis results of this paper, the fire and explosion risk of hydrogen fuel vehicles could be identified and the corresponding emergency disposal technolygy could be used to prevent and control the different accidents. In the future, numerical simulation should be adopted to further investigate the accident modes and accident evolution rules of hydrogen fuel vehicles, and to propose more effective emergency disposal technolygy.

REFERENCE

1. Abul, Q.A., Angelina, F.A., Muhammad, M.M., et al., People Purchase Intention towards Hydrogen Fuel Cell Vehicles: An Experiential Enquiry in Malaysia, *International Journal of Hydrogen Energy*, **41**, No. 4, 2016, pp. 2117-2127.

2. Chol, Y., Jang, G., Kim, S., et al., Fire Safety Evaluation of High Pressure Hydrogen System for FCEV, *Trans of the Korean Hydrogen and New Energy Society*, **20**, No. 3, 2009, pp. 188-193.
3. Watanabe, S., Tamura, Y. and Suzuki, J., The New Facility for Hydrogen and Fuel Cell Vehicle Safety Evaluation, *International Journal of Hydrogen Energy*, **32**, No. 13, 2007, pp. 2154-2161.
4. Vudumu, S.K., Safety Risks of Hydrogen Fuel for Applications in Transportation Vehicles, Center for Transportation Infrastructure and Safety Report No. NUTC-R203.
5. Song, Y.N., TNT Equivalent Method Predicts the Consequence That Some Petrochemical Industry Equipment Explodes, *Open Journal of Safety Science & Technology*, **1**, No. 3, 2005, pp. 66-68.
6. Unified Facilities Criteria (UFC), Design of Buildings to Resist Progressive Collapse, Washington DC: Department of Defense, UFC 4-023-03, 2013.
7. Henrych, J., Abrahamson, G.R., The Dynamics of Explosion and Its Use, 1979, Elsevier Science & Technology, New York.
8. NATO, Manual of NATO Safety Principles for The Storage of Military Ammunition and Explosives AASTP-1, Brussels: NATO, 2006.
9. Bultel, Y, Aurousseau, M, Ozil, P., et al., Risk Analysis on a Fuel Cell in Electric Vehicle Using the MADS/MOSAR Methodology, *Process Safety & Environmental Protection*, **85**, No. 3, 2007, pp. 241-250.
10. Battersby, P.N., Averill, A.F., Ingram, J.M., et al., Suppression of Hydrogen-Oxygen-Nitrogen Explosions by Fine Water Mist: Part 2. Mitigation of Vented Deflagrations, *International Journal of Hydrogen Energy*, **37**, No. 24, 2012, pp. 19258-19267.