EVS25
Shenzhen, China, Nov 5-9, 2010

Design and operation of the hydrogen supply chain for fuel-cell vehicles in Expo Shanghai 2010

Pan Xiangmin[1], Lv Hong[1], Zhou Wei[1], Ma Jianxin[1], Gao Dingyun[2]

[1]*Clean Energy Automotive Engineering Center, School of Automotive Studies, Tongji University*
4800 Caoan Road, Shanghai, 201804, P.R.China
[2]*Shanghai Sunwise Energy Systems Co., Ltd., 10 F(B), Yujia Buliding No.1336 Huashan Road*
Shanghai, 200052, P.R.China
E-mail: panxiangmin@tongji.edu.cn

Abstract

During the Expo Shanghai 2010, 196 fuel-cell vehicles (FCVs) were used to transport visitors in and around the Expo Site. To ensure a reliable fuel supply to these FCVs, a well-designed hydrogen supply chain was established, including an industrial by-product hydrogen purification facility, two fixed hydrogen refueling stations and two mobile hydrogen refueling stations. This paper describes the design of this hydrogen supply chain. The experiences, learnings and quantitative findings from the operation of this hydrogen infrastructure are also presented. In general, the hydrogen supply chain performed well in terms of hydrogen quality and the stations availability. The fact that the FCVs were refueled over 20000 times without major incidents can clearly be seen as a success.

Keywords: Hydrogen supply chain, fuel-cell vehicle, hydrogen refueling station

1 Introduction

Hydrogen is envisioned to be the future fuel for transportation. It is clean and efficient if it is used to power fuel cell propulsion. Research programs for the implementation of a hydrogen-based transportation system are already running in many countries, and the first practical applications are expected by 2015-2030[1].

During the Expo Shanghai 2010, which last 184 days from May 1st to Oct. 31st, over 1000 clean-energy vehicles are used to transport visitors in and around the Expo Site. Among the vehicles there are 196 fuel-cell vehicles (FCVs), including 9 fuel-cell buses, 90 fuel-cell cars and 100 fuel-cell sight-seeing cars. It is another large-scale FCVs demonstration project in China after the FCVs debuted in Beijing Olympics 2008, and it is also almost the biggest field trial of hydrogen and fuel cells in public transport worldwide.

To ensure a reliable fuel supply to these FCVs, a well-designed hydrogen supply chain was established in Shanghai. This paper describes the design of this hydrogen supply chain. The experiences, learnings and quantitative findings from the operation of this hydrogen infrastructure are also presented.

2 Description of the hydrogen supply chain

According to earlier plans, 196 FCVs demonstrated during Expo will be divided into three groups, 100 sight-seeing cars will run in the

Expo Site, 50 fuel-cell cars and 6 fuel-cell buses will run around and in the Expo Site, and the other 40 fuel-cell cars will run around the Shanghai International Automotive City, north-west of Shanghai. The maximum estimated hydrogen demand of the FCVs is 600 kg/day.

Considering the regional hydrogen demand and the siting problem for fixed hydrogen refueling station, a hydrogen supply chain was designed and established to ensure a reliable fuel supply to these FCVs. This hydrogen supply chain consists of an industrial by-product hydrogen purification facility, two fixed hydrogen refueling stations and two mobile hydrogen refueling stations, as shown in Fig. 1.

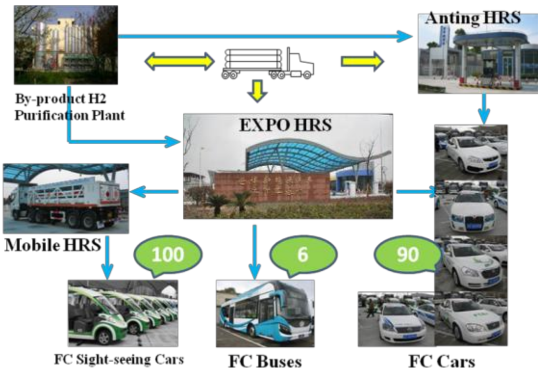

Figure 1: Schematic diagram of hydrogen supply chain in Expo Shanghai 2010

Hydrogen is produced in a by-product hydrogen purification plant, and transported by tube trailers to Anting Hydrogen Refueling Station (Anting HRS) and Expo Hydrogen Refueling Station (Expo HRS). Located in Shanghai International Automotive City, Anting HRS is the first one in Shanghai, and had been operated since 2007. The Expo HRS is newly designed and built in the vicinity of the Expo Site. Fuel-cell cars and buses that running outside the Expo Site can be refueled in both stations. For security reason and mileage limit, the sight-seeing cars can not go out the Expo Site. Therefore, two mobile hydrogen refueling stations were developed so that they can move into the Expo Site to fuel the sight-seeing cars, and the mobile stations are replenished with hydrogen in the Expo HRS.

2.1 Hydrogen production facility

Currently, there is no any large plants specialized in hydrogen production in Shanghai. But Shanghai has plenty of by-product hydrogen resources that can be utilized to fulfill the near to middle term needs. The majority of this byproduct hydrogen comes from two companies: Shanghai Baoshan Iron & Steel Corporation (SBISC) and Shanghai Coking & Chemical Corporation (SCCC). The cost analysis results showed that by-product can be a sound hydrogen source as hydrogen utilization cost is lower than electrolysis and natural gas reforming option; and the capital investment of truck-in station is also lower than that of electrolysis and natural gas reforming station[2].

In 2005, Tongji University has cooperated with SCCC in building a demo coking gas purification facility in SCCC. Using the membrane separation technology and pressure swing adsorption (PSA) technology, by-product hydrogen can be extracted from feedstock such as coking gas, H2-rich syngas and off-gas from methanol synthesis. The hydrogen production capability of the demo facility is 120 Nm^3/hr. In order to meet the demand of hydrogen during the Expo, the demo facility was expanded by adding a second unit. With more than 85% recover rate and 99.99% purity, the new unit has a hydrogen production capability of 280 Nm^3/hr (600 kg/day), which cover the estimated hydrogen demand of the FCVs in Expo, therefore, the old unit can be used as a backup unit.

2.2 Fixed hydrogen refueling stations

Anting HRS and Expo HRS have the same basic process as shown in Fig. 2. By-product hydrogen is delivered to station in tube trailers at no more than 20MPa, compressed to more than 40MPa, and stored in an array of high pressure vessels. As vehicles arrive at the dispenser, priority valves inside the dispenser cascade fill hydrogen to the vehicle tank from low pressure bank, medium pressure bank and high pressure bank to a settled pressure of 35MPa.

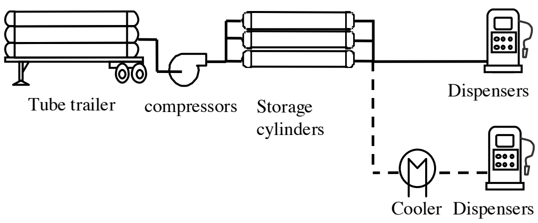

Figure 2: Basic diagram of delivered hydrogen station utilizing by-product hydrogen

Among the FCV fleet refueled in Expo HRS, there are 20 fuel-cell cars are installed with type IV vessel. Type IV vessel has demerits related to problems such as plastic liner leaks, defects and the delamination between plastic liner and the composite wrapping materials caused by the temperature rise during hydrogen fueling process[3]. Therefore, in Expo HRS, a chiller was installed to cool down the hydrogen gas to -20℃ to satisfy the fueling specification for these cars. This is showed in Fig. 2 as dash line.

The fixed hydrogen refueling stations were designed to have good flexibility in hydrogen storage capacity and compressor capacity to meet the uncertain demand. Table 1 lists the characteristics of Anting HRS and Expo HRS.

Table 1: Characteristics of the refueling station units

		Anting HRS	**Expo HRS**
Tube trailer number		2	3
Comp-ressor	type	Diaphragm	Diaphragm
	number	2	4
	capacity (kg/h)	40	80
H2 storage size (kg)		180	300
H2 storage pressure (MPa)		41.4	43.8
Filling pressure		35	35
Dispenser / Hose number		1 / 2	4 / 7

Anting HRS has 9 storage cylinders with a capacity of 180kg hydrogen at 41.4MPa, and Expo HRS has 15 storage cylinders with a capacity of 300kg hydrogen at 43.8MPa. Counting the tube trailer storage capacity, their maximum hydrogen storage capacity will up to 800kg and 1200kg respectively. Anting HRS is equipped with two diaphragm compressors that can run separately or simultaneously. Expo HRS is designed with four sets of compressors, which can operate in any combination to meet the changing needs of filling, and maintenance could be performed on one unit while the others are operating.

Anting HRS has a two hose dispenser with specific nozzles for cars and buses. In Expo HRS, there are four dispensers, including one cold-fill dispenser and three cascade-fill dispensers. The cascade-fill dispensers are domestic designed and developed, and each of them equipped with two hoses. Totally 7 hoses means that the Expo HRS can serve 7 FCVs simultaneously, that makes the Expo HRS become almost the world's largest hydrogen refueling station currently.

When Anting HRS was designed and built in 2006-2007, there was no fully promulgated Chinese standards exist specifically for vehicle hydrogen fueling stations, therefore an amalgamation of vehicle CNG fueling station standards (GB 50156) and industrial Hydrogen Filling Station standards (GB 50177) was utilized and the system was approved by local permitting authorities. Based on the experience in building Anting HRS, Tongji University collaborated with Shanghai Xin'ao Jiuhuan Vehicle Energy Co. in drafting a Shanghai local code for hydrogen refueling station. This local code (DGJ08-2055-2009) was approved and promulgated in March 2009, and it became a key factor for the Expo HRS project to be implemented. Moreover, quantitative risk assessment (QRA) was used to quantify the risk around hydrogen stations and support the communication with authorities during the permitting process[4].

2.3 Mobile hydrogen refueling stations

The transportable hydrogen refueling stations are designed to support early hydrogen FCV initiatives, and help establish the foundation of a hydrogen refueling network. With the support of the National High Technology R&D Program (the 863 Program), Tongji University and Shanghai Sunwise Energy System Co. had developed three generation of mobile hydrogen refueling stations, which greatly supported the R&D of FCV in Shanghai from 2004 to 2009. Moreover, a national industrial standard for mobile hydrogen refueling station (QC/T 816-2009) was developed by the project team and promulgated in Nov. 2009.

The two mobile hydrogen stations used in Expo belong to the third generation. This trailer-mounted hydrogen refueling station comprises several subsystems, including hydrogen compression, storage, and dispensing and safety system. Each mobile hydrogen station has a hydrogen storage capacity of 90kg at 43.8MPa, and is equipped with two dispensers to provide 35MPa refueling service.

Through integrative design of the mobile station and fixed station, the small and mobile one (daughter) can be replenished with high pressure hydrogen in the big and fixed one (mother), then the mobile station can supply hydrogen to vehicles away from fixed hydrogen stations. Such Mather-daughter operation mode is very flexible and particularly suitable for demonstration activities in the earlier commercializing stage of FCVs. Like during the Expo demo, two mobile hydrogen refueling stations enter the Expo Site to fuel the fuel-cell sight-seeing cars in every night, as shown in Fig. 3, and turn back to the Expo station in the morning. Through this Mather-daughter operation mode, the service radius of Expo HRS was expanded, the siting difficulty for building more fixed station was avoided, and the capital cost of hydrogen infrastructure was reduced, too.

Figure 3: Photograph showing the mobile station serving the fuel-cell sight-seeing cars

3. Operation of the hydrogen supply chain

After more than a year of construction, the new expanded by-product hydrogen purification facility, Expo HRS and two mobile HRS were put into trial operation in March and April 2010. Together with the Anting HRS, they formed the first hydrogen refueling network in China. While supplying hydrogen to FCVs demonstrated in Expo, the hydrogen infrastructure itself is to be demonstrated and validated. Through operation of these hydrogen facilities, the real-world data will be collect and evaluate to address technical and safety issues.

3.1 Hydrogen production facility

The most important thing for the by-product hydrogen purification facility is to control the hydrogen quality. To ensure the hydrogen quality, the product gas was sampled and analyzed every two weeks. The purity of the by-product hydrogen is generally higher than 99.99% (V/V), and the impurities content should meet the requirements as shown in table 2.

The fuel cell tests and FCV running tests results verified that the purified by-product hydrogen fully meets requirements of FCV. It can be seen from Fig. 4 that the performance of 5kW stack remains stable during 500 hours driving cycle test using by-product hydrogen.

Table 2: By-product hydrogen quality index

Impurities	limits
Carbon monoxide, CO	≤1ppm
Carbon dioxide, CO2	≤1ppm
Total hydrocarbons, HC	≤1ppm
Oxygen, O2	≤1ppm
Inert Gases, N2+Ar+He	≤60ppm
Total Sulfur compounds	≤0.01ppm
Total halogenated Compounds	≤0.01ppm
Ammonia, NH3	≤0.01ppm
Particulates	none

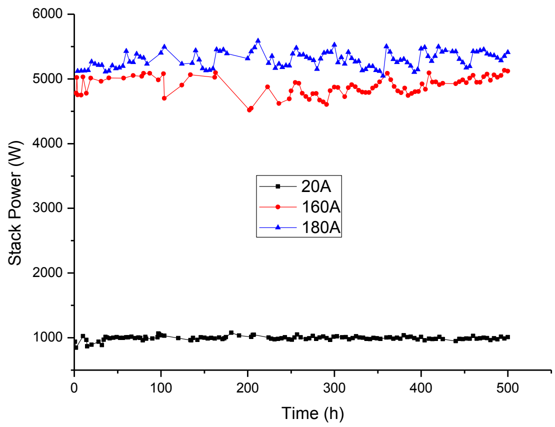

Figure 4: Driving cycle durability test of a 5kW fuel cell stack using by-product hydrogen

3.2 Hydrogen refueling stations

Most of the Expo FCVs were developed and manufactured in Shanghai International Automotive City (Anting Town), so that they could get hydrogen from the nearby Anting HRS. As the Expo was coming, the filling frequency and filling quantity of Anting HRS both reached the highest value of its history. The statistics shows that the vehicles were refueled 423 times and consumed 1047kg of hydrogen in Anting HRS in April 2010.

It can be seen from Fig. 5 and Fig. 6 that the amount of hydrogen supplied in Anting HRS dropped to average about 340kg per month and about 240 vehicle fillings happened in each month since May. This could be expected because that only 40 FCVs were left in Shanghai International Automotive City when the Expo Shanghai was opened in May 2010, 100 fuel-cell sight-seeing cars moved into the Expo Site, and the other 50 fuel-cell cars and 6 fuel-cell buses moved to the FCV maintenance base 2.4km away from the Expo Site. The fleet of sight-seeing car

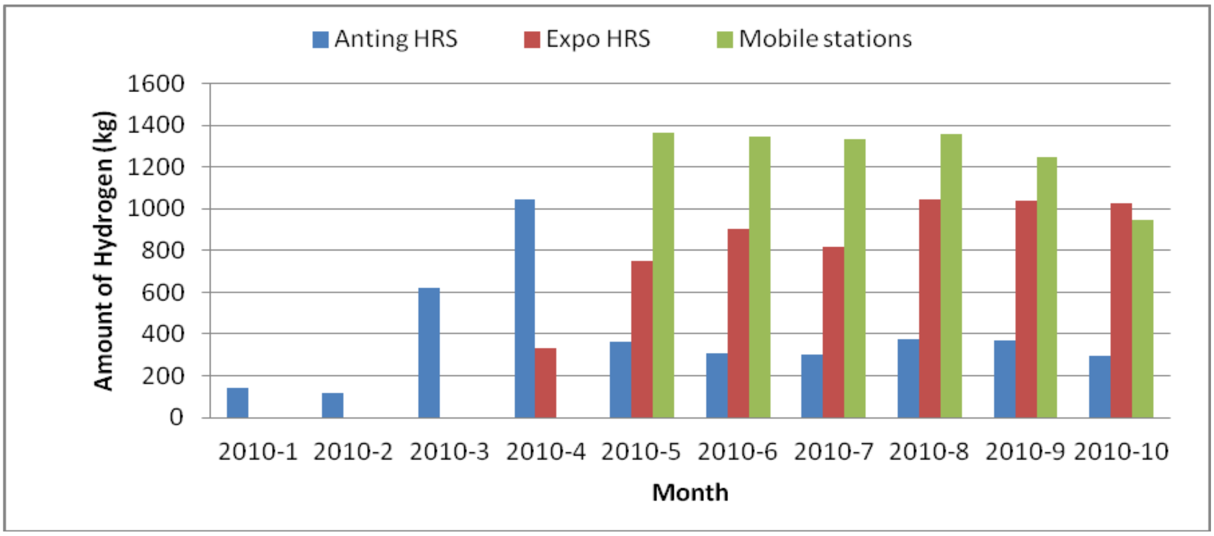

Figure 5: Statistics of H2 filling amount in hydrogen refueling stations

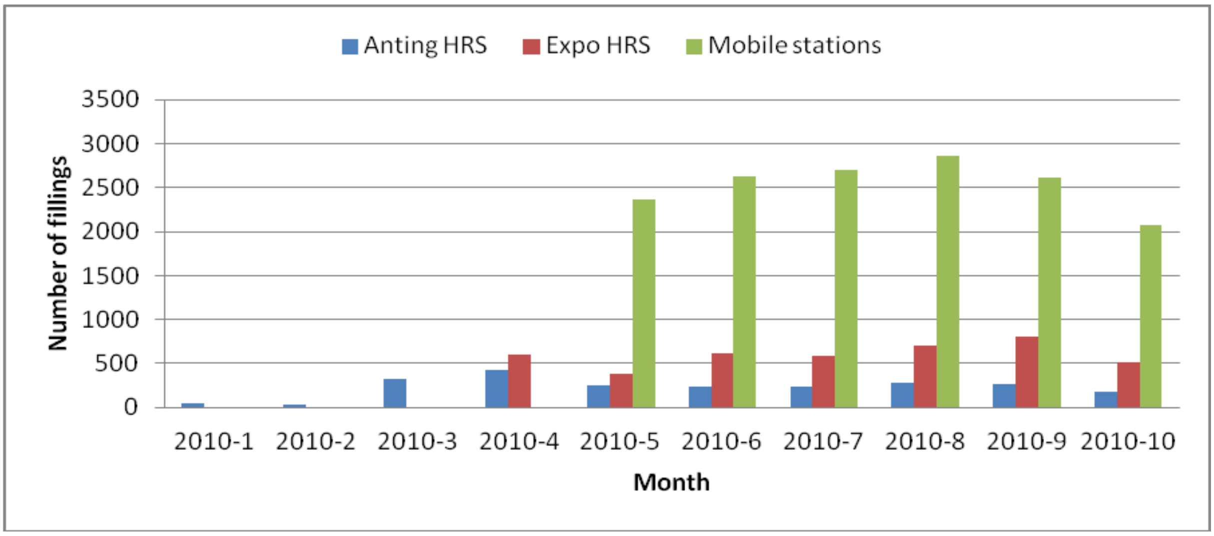

Figure 6: Statistics of vehicle fillings in hydrogen refueling stations

was serviced by two mobile hydrogen stations and the Expo HRS supplied hydrogen to the others.

During its trial operation in April, the Expo HRS fuelled vehicles 596 times and 334kg H2 was dispensed. From May to October, average about 600 vehicles were refueled and about 900kg H2 was dispensed in each month in Expo HRS.

The performance of the mobile hydrogen stations is most outstanding. Average over 2500 times filling and over 1200kg H2 dispensing per month were achieved. It was reported that more than 70 million visitors had entered the Expo Site by Oct 25, the huge number of visitors make the sight-seeing cars very popular so that the mobile hydrogen stations must keep in running with full capacity every day.

Table 3: Summary of FCVs fillings from May to October 2010

	Number of fillings	*Amount of H2 filled (kg)*
FC buses	295	2574
FC cars	4756	5027
FC sight-seeing car	15251	7603
Total	**20302**	**15204**

However, it is also can be found that the hydrogen demand is far lower than estimated, mostly because the FC buses consumption is far lower than planned. The FC buses were only refueled 295 times and consumed over 2574kg of hydrogen, as shown in Table 3.

3.3 Availability of the hydrogen refueling stations

Availability of the station could be defined as the ratio of time that the station was operational to the duration of the evaluation period; "operational" meaning that the station was in operation and could supply hydrogen to the FCVs. During the Expo demonstration, the availability of Anting HRS and Expo HRS are both 99%, and the availability of the two Mobile Stations is 100%.

The lessons learned from infrastructure operation in the project CUTE (Clean Urban Transport for Europe) showed that the hydrogen compressors and dispensing equipments were the most critical components of the station units with regard to downtime[5]. Similar experience was gained in our project. A hydrogen leak incident happened to the dispenser of Anting HRS led to a half day close of the station. As for the Expo HRS, a broken fuse caused a wrong ESD (Emergency Shut Down) alarm and led to a half day downtime, too.

The Mother-daughter mode was proved to be very effective and reliable. Normally, the mobile station entered the Expo Site after 0:00, spent two to three hours in refueling the Sight-seeing cars, and then turned back to the Expo HRS to be refilled with hydrogen in the early morning, which is an idle time for the fixed station. Inspection and maintenance work could be undertaken in daytime to keep the mobile station in good conditions.

To ensure the safety and availability of the stations, a series of rules and regulations were formulated and implemented, including the instructions for operating and maintaining equipments, regular leakage testing and safety inspecting. In addition, a SCADA (Supervisory Control and Data Acquisition) system was developed to monitor all stations condition. The rapid response to incidents is another important factor for a successful operation.

4. Conclusions

In this paper we have presented the design and operation of the hydrogen supply chain for FCVs demonstration in Expo Shanghai 2010.

In general, the hydrogen supply chain performed well in terms of hydrogen quality and the stations availability. The fact that the FCVs were refueled almost 20000 times without major incidents can clearly be seen as a success.

This hydrogen supply chain will continue operation after the Expo, more data will be collected, and more lessons will be learned. All this gains will be helpful to develop technologies, codes and standards, as well as policies, and therefore advance the deployment of hydrogen infrastructure.

Acknowledgments

This work is supported by Shanghai Expo Science and Technology Project (09dz0580100) and Program of International S&T Cooperation (2010DFA64080).

References

[1] Shane Stephens-Romero, G. Scott Samuelsen, *Demonstration of a novel assessment methodology for hydrogen infrastructure deployment,* International Journal of Hydrogen Energy, ISSN 0360-3199, 34(2009), 628-641.

[2] Liu Shaojun, *Cost analysis of hydrogen refueling station based on Techno-economic model,* Thesis for the degree of Master of Dcience, Tongji University, 2007.

[3] Sung Chan Kim, Seung Hoon Lee, Kee Bong Yoon, *Thermal characteristics during hydrogen fueling process of type IV cylinder,* International Journal of Hydrogen Energy, ISSN 0360-3199, 35 (2010), 6830-6835.

[4] Li Zhiyong, Pan Xiangmin, Ma Jianxin, *Quantitative risk assessment on a gaseous hydrogen refueling station in Shanghai*, International Journal of Hydrogen Energy, ISSN 0360-3199, 35 (2010), 6822-6829.

[5] K. Stolzenburg, V. Tsatsami, H. Grubel, *Lessons learned form infrastructure operation in the CUTE project*, International Journal of Hydrogen Energy, ISSN 0360-3199, 34(2009), 7114-7124.

Authors

Dr. Pan Xiangmin is an associate professor of the Clean Energy Automotive Engineering Center, Tongji University. He works in the field of hydrogen technology, especially in hydrogen infrastructure. He obtained his Ph.D at East China University of Science and Technology in March 2006.