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ABSTRACT

Thousands of public hydrogen fueling stations are needed to support the early Fuel Cell Electric Vehicle (FCEV) market in the U.S.; there are currently 12. The California state government has been the largest investor of the hydrogen fueling infrastructure funding 9 permanent stations currently open to the public with 48 more in development costing anywhere from $1.8M-$5.5M each. To attract private investors and decrease dependence on government funding, a low-cost, mobile hydrogen dispensing system must be developed. This paper describes a transportable hydrogen fueling station that has been designed for $423,000 using off-the-shelf components, less than 23% of the capital cost of current stations. It utilizes liquid hydrogen storage and a novel cryogenic compression system which can be factory built for high volume, rapid production. These stations would be contained in a standard 40' ISO shipping container to move/expand with demand and dispense hydrogen at a price of $9.62/kg. This paper presents the mechanical design and operation of the fueling station. A complete report including an economic analysis and safety features is available at: http://hydrogencontest.org/pdf/2014/WSU_2014_HEF_CONTEST.pdf.

Keywords: Fuel station; Infrastructure; Fuel Cell Electric Vehicle; Cryo-compression; Liquid delivery; Cryogenics

1. INTRODUCTION

Hydrogen stations currently open in the U.S. for fueling Fuel Cell Electric Vehicles (FCEV) range from $1.8-$5.5 million to construct [1]. The cost is a result of each station demonstrating a unique design with virtually no standardization. These stations are permanent installations with fixed capacities that cannot easily adapt to the changing demand for hydrogen (H_2). The high cost and lack of flexibility of these stations creates high risk for private investors putting the financial support of the hydrogen fueling infrastructure on government agencies.

Estimates show 4,500-9,200 stations are required in metropolitan areas across the U.S. to support early adopters of FCEVs and initiate their successful penetration into the household vehicle market [2]. Currently, only 12 public hydrogen fueling stations exist for FCEVs [3]. That means a minimum of $8 billion would have to be invested to reach 4,500 hydrogen stations at the lowest current cost per station. It would take the U.S. Department of Energy almost 65 years to fund that amount based on the entire 2013 Hydrogen and Fuel Cell budget of $123.3 million [4].

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Hydrogen station cost reductions must be realized to attract private investors and reduce the dependence on government subsidies to successfully support the imminent commercialization of FCEVs.

Lowering the cost of distributing, storing, and dispensing hydrogen that is produced at a central plant is difficult given its physical properties and strict safety regulations. Compressing hydrogen at the production and dispensing stages also adds to station capital and operating costs. Typical 35 MPa and 70 MPa H_2 compressors cost $50,000-$140,000 each and consume 2-4 kWh/kg of electricity (compressing 20-350 bar) [5]. Hydrogen gas heats up when expanded requiring high pressure hydrogen chillers to precool before filling FCEV fuel tanks which cannot exceed 85 °C. The hydrogen combustibility range of 4-75% in air requires additional safety equipment increasing the station cost. Modern tube trailers for gaseous H_2 delivery are rated for 35 MPa which equates to 809 kg of H_2 and cost $633,750 [6]. Cryogenic tanker trucks for liquid hydrogen (LH_2) delivery have a 4000 kg H_2 capacity, cost $600,000, and have been established for decades [7].

At present, industry experts are focused on supply chains, hydrogen compression, high pressure storage components, and standardizing station designs among other things to reduce station costs [1]. One consensus is that early commercial stations deployed in 2014-2016 will output 333 kg/day on average and cost approximately $2.8 million each. That is a 62% decrease in capital cost per capacity from current stations benefitting mostly from economies of scale. Advances in carbon fiber cylinders hope to raise the storage capacity of gaseous H_2 delivery tube trailers to 1155 kg at 54 MPa by 2020 to meet anticipated demands [6]. Higher efficiency centrifugal compressors would replace existing reciprocating ones and improvements on centrifugal technology would lower costs further.

The mass deployment of H_2 fueling stations for early support of the FCEV market depends on a low-cost, modular design. In this paper the design for a transportable hydrogen fueling station is presented that would use readily available components at a cost of $423,000. It would use liquid hydrogen storage and a unique two step dispensing process that utilizes LH_2 properties to minimize operating and equipment costs. Each station could be setup in less than 24 hours, operate autonomously, and require only liquid hydrogen delivery, 208 V power, and city water. Fuel stations can dispense at least 100 kg/day of 70 MPa hydrogen at a cost of $9.62/kg assuming a delivery cost of $7/kg. A rendering of the H_2 fuel station is shown in Figure 1.

FIGURE 1. Rendering of a transportable hydrogen fueling station.

2. HYDROGEN FUEL STATION DESIGN AND OPERATION

The mobile H_2 fueling station was designed to fit entirely within a standard 40’ ISO shipping container and delivered via semi truck. This H_2 station has been designed to fuel two 70 MPa FCEVs simultaneously but could easily fuel 35 MPa vehicles with the addition of a 35 MPa dispensing nozzle. This system has been designed assuming 0.5 MPa, -246 °C liquid hydrogen delivery and a FCEV fuel tank capacity of 5 kg. These assumptions are not critical to the design and will only have a minor affect on the gaseous hydrogen storage volumes.

2.1 DISPENSING HYDROGEN TO A FCEV

The fueling station dispenses H_2 in accordance with SAE J2601 standards and has been designed from the customer’s perspective to safely fill FCEVs using steps similar to a gasoline station. A touch-screen user interface will be used to accept payment and provide step-by-step instructions through the filling process. A WEH Technologies TK17 nozzle which functions similar to a gasoline station nozzle will be manually connected to the FCEV fill port. For safety, these nozzles only dispense to vehicles rated for 70 MPa H_2 and are equipped with breakaway coupling in case of excessive strain on the hose.

When a fill-up is requested, the system command module will determine the amount of hydrogen in the vehicle tank, referred to as the state of charge (SOC), using temperature sensors, pressure sensors, and the data uplink in the dispensing nozzle. The initial SOC determines which dispensing process is used: SOC at or above 75% (3.72 kg) requires only “topping-off,” SOC below 75% requires two step dispensing. The topping-off process discharges H_2 from a 112 MPa storage tank to bring the vehicle to 70 MPa and 100% SOC (5kg). The two step process will begin with discharging hydrogen from a 41.4 MPa storage tank until the vehicle reaches a SOC of 75%. The second step will use the same process as topping-off to complete the fill-up. The command module will analyze input from a mass flow meter and pressure sensors while dispensing to determine when the vehicle tank is full.

2.2 COMPRESSION AND STORAGE

The hydrogen dispensing storage tanks described in the previous section will be comprised of fifteen HyPerComp Engineering type-IV pressure vessels (carbon fiber wound with a polymer liner). The 41.4 MPa vessels, referred to as medium pressure (MP) cylinders, will be made up of 6 cylinders plumbed together for a total volume of 787 L. The 112 MPa vessels, referred to as high pressure (HP) cylinders, will have a volume of 62 L each. The station will require three HP cylinders to support the demand of 6 FCEVs per hour and fill two simultaneously due to the time intensive process to recharge a HP cylinder. With this configuration two HP cylinders can be dispensing fuel while one is recharging. A Chart Industries 11,924 L (3150 gallon) insulated cryogenic tank provides bulk storage of liquid hydrogen for the station. It has a capacity of 725 kg and will have to be refilled once a week for the assumed demand of 100 kg/day. The last storage volume in the station design is a type-IV pressure vessel, referred to as the low pressure (LP) cylinder, with a volume of 131 L.

The hydrogen station dispensing system will use a combination of mechanical and cryogenic compression to recharge the storage cylinders. Mechanical compression will be supplied by a Hydro-Pac reciprocating hydrogen compressor for pressure up to 41.4 MPa (6,000 psi). Cryogenic (cryo) compression or autogenesis pressurization is the process of vaporizing a fixed volume of very low temperature liquid. In this system the HP cylinders are filled with LH_2, sealed, and the LH_2 is boiled and heated to -40 °C to obtain a pressure of 112 MPa (16,300 psi). The recharging process will begin after each FCEV fill-up at which point both the MP and HP cylinders will require compressed hydrogen. The pressure in the HP cylinder, which will then be at 70 MPa, will need to be evacuated so it can be refilled with LH_2 and cryo-compressed. The first step will be to open a valve between the HP and MP cylinders to allow H_2 in the higher pressure HP cylinder to flow into the MP cylinders until they reach equal pressure. This initial step will reduce the amount of hydrogen processed by the compressor. The remaining hydrogen in the HP cylinder will then be sent through the reciprocating compressor to recharge the MP cylinders to 41.4 MPa. Once the pressure in the HP cylinder is reduced below 0.5 MPa the valve between the LH_2 storage tank and the HP cylinder will be opened, filling the HP cylinder with liquid hydrogen and cryo-compressed. The MP and HP cylinders will then be fully recharged and ready to fuel another vehicle. A diagram showing the flow of hydrogen through the system is shown in Figure 2.

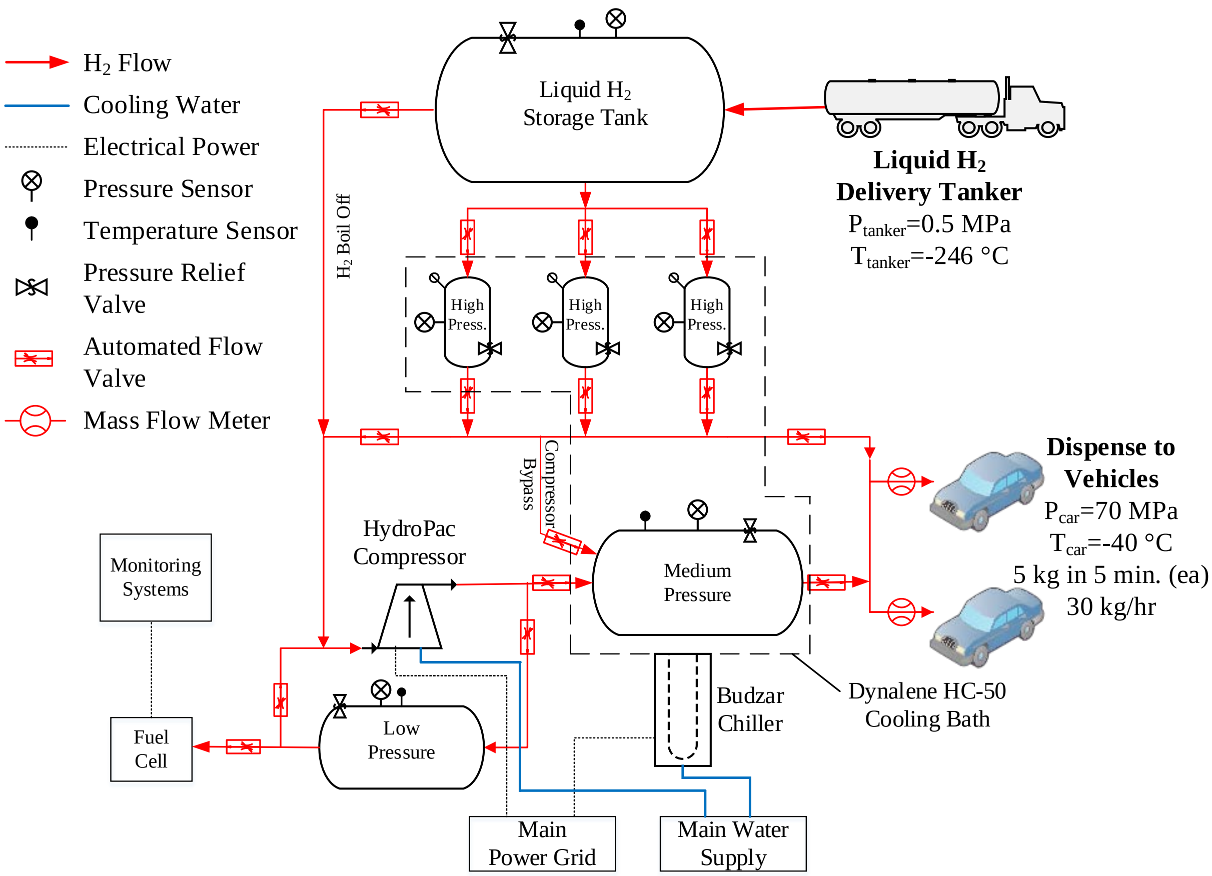

FIGURE 2. Hydrogen fuel station system diagram. Note that medium and low pressure tanks are shown here as single volumes for clarity.

The HP cylinders were sized so that there is no excess hydrogen in the system nor is the system deficient of hydrogen during an average fill-up; the amount of hydrogen remaining in the HP cylinder replaces that which has left the MP cylinders. Thus all of the hydrogen used to charge the HP cylinder will be discharged into the vehicle either directly from the HP cylinder or through the MP cylinders on the next fill-up. It is important to note that this station operates on a batch fill process, a consequence of cryo-compression, and has been optimized for an average case that assumes drivers refuel once they reach a SOC of 25%. For situations that deviate from the assumed average, the low pressure cylinder will act as a buffer volume; storing hydrogen when there is excess and providing additional hydrogen when needed. For example, if a vehicle tank is initially at 75% SOC the HP cylinder will discharge but the MP cylinders will remain full. The remaining hydrogen in the HP cylinder must be removed to prepare for the LH_2 charge but the MP cylinders will already be at capacity. In this case the excess hydrogen will be pumped into the LP cylinder by the reciprocating compressor. In the event that a driver comes in with a SOC below 25%, the MP cylinders have been sized to still bring the vehicle fuel tank up to a SOC of 75%. However, since the remaining hydrogen in the HP cylinder will not fully charge the MP cylinders, hydrogen from the LP cylinder will make up the difference. If the LP cylinder pressure drops below 0.5 MPa, hydrogen vapor from the LH_2 tank will be used. If the LP and MP cylinders all reach capacity, hydrogen will be ran through a 3 kW fuel cell to generate electricity or vented to the atmosphere. The fuel cell will be part of the safety system to provide power to essential monitoring components during grid power failures.

Every storage volume will be outfitted with a temperature sensor, pressure sensor, and pressure relief valve. A system of high-pressure automated flow valves governed by a logic-based command module will control the flow and dispensing of hydrogen. Mass flow meters will track how much hydrogen has been dispensed to each vehicle. All of these components will allow the station to operate autonomously and provide real-time feed back to a remote operator for monitoring and control if needed. A footprint of the 40' fuel station container showing the major system components is depicted in Figure 3.

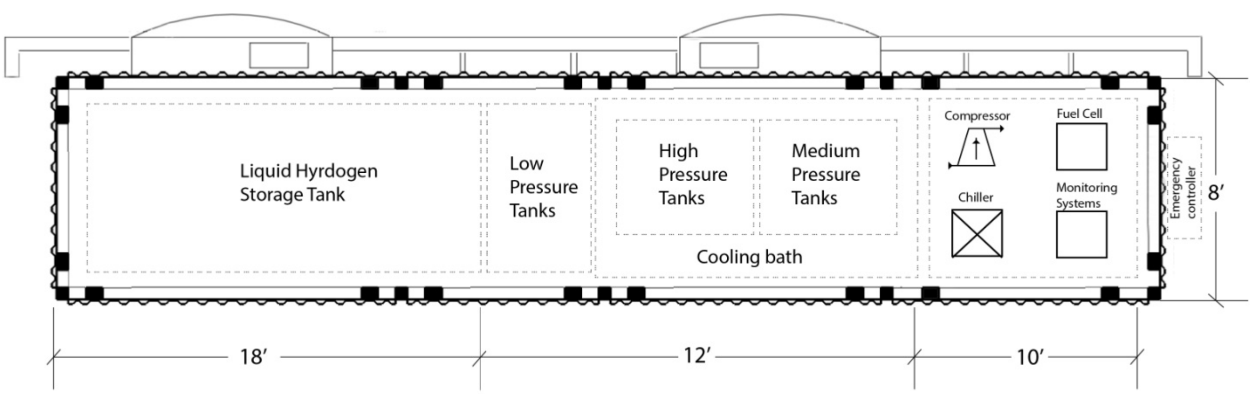

FIGURE 3. Component layout of the hydrogen station.

2.3 THERMAL MANAGEMENT

The thermal management system for the transportable hydrogen station is designed to insure refueling times comparable to gasoline stations and reduce operational costs. Hydrogen gas must be precooled before being dispensed because its temperature increases as it expands and FCEV composite tanks cannot exceed 85 °C. Tests have shown that hydrogen gas precooled to -40 °C can fill 7 kg FCEV tanks from 2-70 MPa in less than 5 minutes for ambient temperatures up to 45 °C [8]. If hydrogen is compressed on demand or held at high pressure and ambient temperature, as is the case with many H_2 stations, it must be ran through a high pressure hydrogen refrigeration unit to cool to -40 °C before dispensing which adds several minutes to each fill-up and complexity to the system. The transportable hydrogen station will mitigate the precooling time by holding the MP and HP cylinders in a cooling bath maintained at -40 °C by a Budzar Industries industrial chiller. This bath will also create a thermal link between the cylinders so the heat added to the MP cylinders by the compressor can be absorbed by the cold LH_2 charge in the HP cylinders, promoting cryo-compression. Additional heat can be added to the HP cylinders by an electric heater to increase the vaporization rate when there is high fueling demand.

3. COST BENEFITS OF DESIGN

The main objective of the transportable H_2 station design is to conceive the lowest cost dispensing system using components and services that are widely available now to provide a widespread station network for the immerging FCEV market. A comparison was made between onsite steam methane reforming (SMR), onsite electrolysis, and centralized offsite production to determine the lowest cost hydrogen production method for a near-term, large network of hydrogen stations. A National Renewable Energy Laboratory (NREL) report supports offsite production for the transportable hydrogen station design (100 kg/day capacity, LH_2 delivery) by showing that station capital costs would be 20% lower than onsite SMR and 15% lower than onsite electrolysis using current technology [1]. Centralized offsite production uses economies of scale to deliver the lowest cost of hydrogen and therefore was selected in this station design. Furthermore, commercial hydrogen plants already exist near metropolitan areas across the U.S. so no new hydrogen sources would have to be built initially.

There are three ways to transport hydrogen from a central production plant to fueling stations; (1) compressed gas tube trailers, (2) cryogenic liquid tanker trucks, or (3) gas pipelines. Liquid hydrogen delivery was chosen for this design because previous reports show that it has the lowest cost of delivery between the 3 options [1,6]. LH_2 delivery accounts for 80-90% of hydrogen currently provided by merchants so the infrastructure is well established to meet hydrogen fueling station demands [9].

The transportable hydrogen station design uses LH_2 storage because the thermodynamic properties of liquid hydrogen can be utilized to provide lower capital and operating costs compared to gaseous storage. Cryo-compression paired with a 41.4 MPa (6,000 psi) compressor lowers the station's compressor energy consumption by 63% and capital cost by $85,000 compared to using an 82.7 MPa (12,000 psi) compressor.

This station was completely designed using actual vendor quotations totaling $423,000 of off-the-shelf components. This station would cost 23% less than typical permanent hydrogen stations of similar capacity. An operational cost analysis shows that this design could fuel vehicles for $9.62 per kilogram of H_2 (assuming a $7/kg delivery cost), which is roughly $48 for a 5 kg fuel tank with a range of approximately 300 miles. This price of hydrogen is equivalent to paying $4 per gallon of gasoline for a car that gets 25 mpg.

4. CONCLUSIONS AND RECOMMENDATIONS

The hydrogen fueling infrastructure has historically been technically infeasible and too expensive but this mobile H_2 station challenges that convention. This design utilizes cryo-compression to reduce component and energy costs. Cryo-compression is scarcely used in industry but has been technically validated for vehicle applications by Aceves *et al*. [10] and the U.S. Department of Energy's Hydrogen Program [11]. It is recommended that a fully functional prototype be built to prove the functionality of this station design before committing to commercialization.

This paper focuses primarily on the mechanical design and operation of the transportable H_2 fueling station. A complete report including an economic analysis and discussion of safety, regulations, and environmental impacts can be found at: http://hydrogencontest.org/pdf/2014/WSU_2014_HEF_CONTEST.pdf.

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