III.1 Hydrogen Delivery Infrastructure Analysis

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Project Start Date: October 2007
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

Evaluate hydrogen delivery and refueling concepts that can reduce hydrogen delivery cost towards meeting the delivery cost targets.

Fiscal Year (FY) 2014 Objectives

- Evaluate the potential of novel delivery concepts for refueling cost reduction
- Evaluate the role of high-pressure tube-trailers in reducing compression cost at hydrogen refueling stations (HRS)
- Incorporate limitations imposed by SAE International (SAE) J2601 refueling protocol in the modeling of HRS

Technical Barriers

This project directly addresses Technical Barriers A, B, and E in the Hydrogen Delivery section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration (MYRD&D) Plan. These barriers are:

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis

(B) Reliability and Costs of Gaseous Hydrogen Compression

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Technical Targets

The project employs the Hydrogen Delivery Scenario Analysis Model (HDSAM) and Hydrogen Station Cost Optimization & Performance Evaluation (H2SCOPE) simulation tools to investigate current and novel hydrogen delivery technologies and pathway options with the potential to meet the cost targets specified in the FCTO MYRD&D Plan, and to assist with defining R&D areas that can bridge current and future performance and cost targets of major delivery and refueling components.

Contribution to Achievement of DOE Hydrogen Delivery Milestones

This project contributes to achievement of the following DOE milestone from the Hydrogen Delivery section of the FCTO MYRD&D Plan:

- Task 2.5: Down select two to three H_2 pressurization and/or containment technologies that minimize delivery pathway cost for mid-term markets. (2Q, 2014)

FY 2014 Accomplishments

Developed and simulated a novel tube-trailer consolidation scheme that can reduce the capital cost of compression at refueling station by more than 50% of current values, working toward the DOE FCTO MYRD&D FY 2015 target of $360,000 for one forecourt compressor at a 1,000 kg/day station.

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INTRODUCTION

From our previous analyses, the refueling station was found to contribute about half of total delivery cost in a mature fuel cell electric vehicle (FCEV) market where the station's capital investment is fully utilized. Furthermore, the refueling station compression constitutes about half of the station installed capital cost. Thus, the focus of our analysis this FY was on identifying opportunities at the refueling station that would reduce its capital cost by developing a significant part of the hydrogen compression upstream of the HRS where the compression equipment would benefit from economies of scale and improved utilization of the capital investment. Compressing hydrogen into tube trailers in terminals adjacent to hydrogen production would satisfy this purpose. Tube trailers are furthermore likely to be the primary means of hydrogen delivery in the near to mid term. This project examined the benefits of operating high-pressure tube trailers at hydrogen refueling stations using the H2SCOPE model. H2SCOPE was developed from first principles by solving physical conservation laws to track temperature, pressure and mass at various points within a refueling station and also inside the FCEV's onboard storage tank. H2SCOPE allowed us to optimize the size of the compressor and cascade buffer storage system at the refueling station while following the SAE J2601 hydrogen fueling protocol. A novel tube trailer consolidation concept was developed and simulated to examine the potential reduction of compression cost at the refueling station through efficient management of the payload of the tube trailer.

We modeled the operation of the refueling station that includes a dispenser which connects and manages the hydrogen flow between the high-pressure buffer storage system and the vehicle tank, a refrigeration unit placed between the dispenser and the high pressure buffer storage system which pre-cools the hydrogen to -40°C for fast refueling, a 250-bar tube trailer that supplies hydrogen to the refueling station, and a compressor which draws hydrogen from the tube trailer to replenish the high-pressure cascade buffer storage system.

Accurate modeling of the compressor performance is key to generating reliable simulation results. Figure 1 shows the PDC 2500/7500 compressor performance curve which was employed in our modeling and analysis. The figure shows the variation in the compressor's throughput with suction pressures. The flow rate varies from about 100 Nm^3/hr @ 20 bar suction to about 900 Nm^3/hr @ 250 bar suction. Maintaining the minimum suction pressure at a high pressure, e.g., above 100 bar, ensures a flow rate above 400 Nm^3/hr, which is about 4 times the flow rate at the rated suction pressure of 20 bar. The proposed tube-trailer consolidation scheme aims to take advantage of this linear relationship between the compressor's suction pressure and flow rate. The consolidation concept maintains a high compressor suction pressure during peak demand hours, thus amplifying the compressor's throughput. A small compressor can therefore be employed to serve a station during its high demand periods, thus reducing the station's capital investment.

In this context, consolidation is the process of compressing hydrogen from one tube trailer vessel into another to maintain high pressure in at least one of the tube trailer vessels that supplies the compressor suction manifold. To maintain a high compressor suction pressure during peak hours, hydrogen is consolidated within the individual pressure vessels mounted on the tube trailer during off-peak hours. This occurs when the compressor is otherwise idle, thus improving the utilization of the compressor.

In general, hydrogen can be consolidated within the tube trailer, when the compressor and pressure vessels on the tube trailer are idle. To simplify the simulation and examine the extreme refueling conditions, we have divided each hour into two periods: A and B. For any hour with number of vehicles n expected to be filled within that hour, A represents the minimum time required to fill all the vehicles back-to-back within that hour, while period B represents the remaining time of that hour. Hydrogen is assumed to be consolidated during period B when all buffer storage banks are at their rated working pressure.

Figure 2 shows the operation of a refueling station with tube trailer consolidation capability during period A of each hour. The vehicle is fueled either by drawing hydrogen from the tube trailer or one of the high-pressure buffer storage banks, while the other (idle) cascade pressure vessel banks

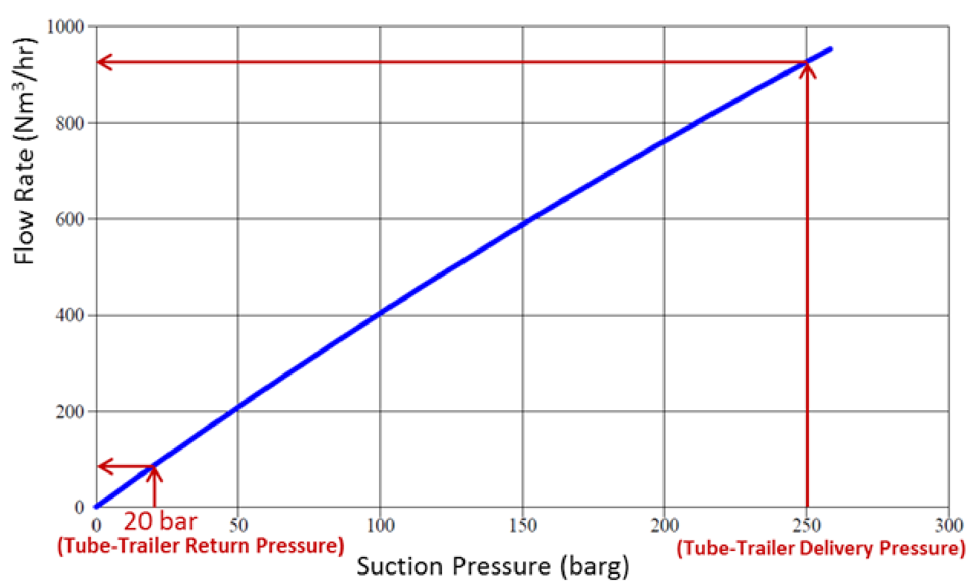

FIGURE 1. Flow Curve of PDC 2500/7500 Compressor

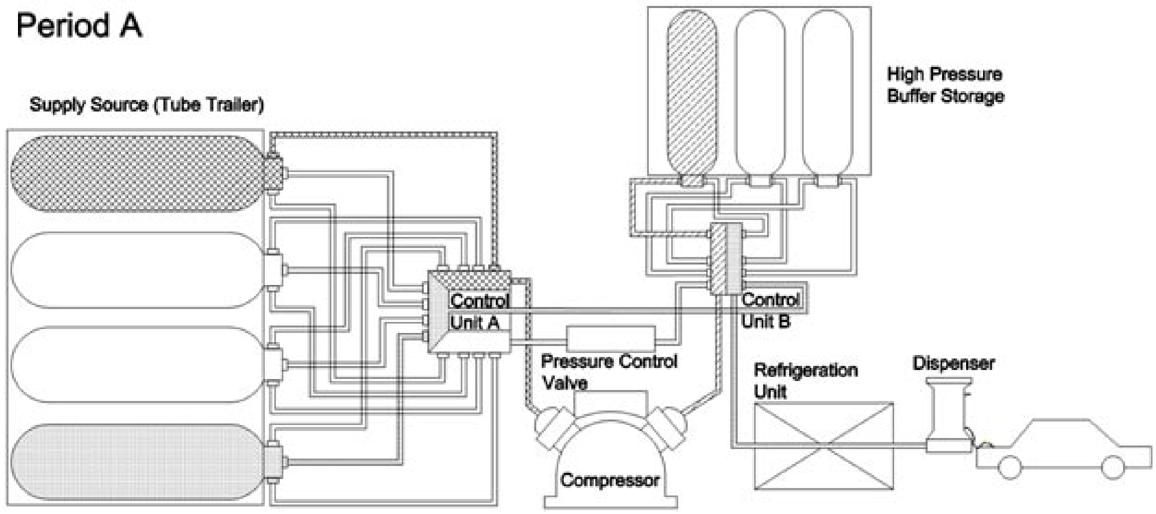

FIGURE 2. Schematic of Station Component Layout and Operation for Period A of Each Hour

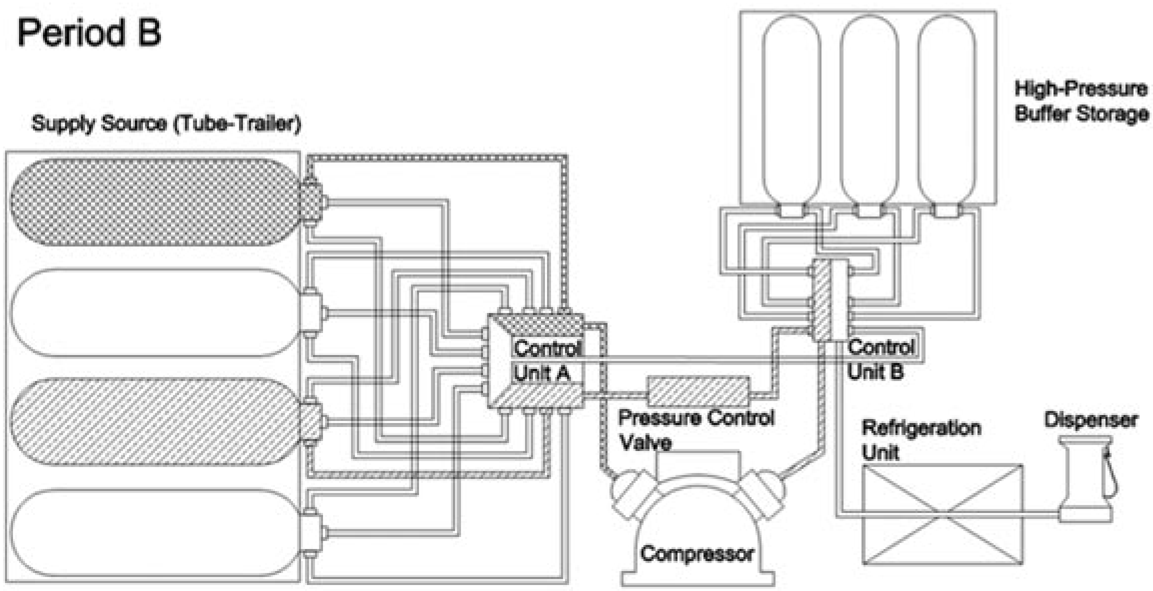

FIGURE 3. Schematic of Station Component Layout and Operation for Period B of Each Hour

are replenished by the compressor that draws hydrogen from the tube trailer vessels. During the period B hydrogen is consolidated in the pressure vessels on the tube trailer by moving hydrogen from the vessels with lower pressure to the vessels with higher pressure as shown in Figure 3. Table 1 shows a summary of the tube trailer operation strategy for a refueling station with and without tube trailer consolidation.

RESULTS

We performed simulations for station capacities of 100, 150, 200, 250, 300, 350, 400, and 450 kg per day. Implementation of the consolidation concept is shown in Figure 4, which illustrates the mass in each pressure vessel on the tube-trailer after every vehicle fill. The horizontal axis represents the number of vehicles filled during the operation of the refueling station, while the vertical axis represents the mass of hydrogen within each of the four vessels mounted on the trailer. An increase in hydrogen mass in a vessel indicates consolidation, while a decrease in hydrogen mass in a vessel indicates drawdown by the compressor to fill the buffer storage bank or to consolidate hydrogen to another vessel on the trailer.

TABLE 1. Summary of HRS Operation Strategy with and without Tube Trailer Consolidation

Operation Strategy Parameter	Tube Trailer Operation Strategy	
	Without Consolidation	With Consolidation
Tube trailer used for initial vehicle fill	No	Yes
Tube trailer hydrogen consolidation	No	Yes
Pressure of selected vessel on tube trailer to fill vehicle tank	NA	Max
Pressure of selected vessel on tube trailer to fill cascade buffer storage system	Min	Max (Period A) Min (Period B)
Pressure of selected vessel on tube trailer for H_2 consolidation	NA	Min
Number of tube trailer vessels	4	4
Tube trailer capacity (H_2 in kg)	640	640
Tube trailer capacity for refueling (vehicles)	123	123

TABLE 2. Summary of Number of Vehicle Fillings with and without Tube Trailer Consolidation

Daily HRS Capacity (kg/day)	# of Vehicles Filled (Tube Trailer Payload Utilization)	
	Without Consolidation	With Consolidation
100	121 (94%)	
150	121 (94%)	
200	21 (not capable of satisfying hourly demand)	110 (86%)
250		110 (86%)
300		110 (86%)
350		109 (85%)
400		109 (85%)
450		109 (85%)

Table 2 shows that a station can satisfy a refueling demand of up to 150 kg/day without tube trailer consolidation, but can satisfy a demand of up to 450 kg/day with tube trailer consolidation. The station operation with the consolidation strategy achieves a high tube-trailer payload utilization of 85% as shown in Table 2. For a 450 kg/day refueling station not employing the consolidation strategy, the compressor capacity at a tube-trailer return pressure of 20 bar would be about 400 Nm^3/h. Quotes from compressor manufacturers show compressor cost increases from about \$300,000 for a 90 Nm^3/h compressor (with the consolidation strategy) to \$750,000 for the 400 Nm^3/h compressor (without the consolidation strategy), implying a compression cost savings of \$450,000 with tube trailer consolidation for that station capacity.

The tube trailer consolidation strategy improves the economics of the station through more efficient utilization of a station compressor that operates more steadily during peak and off-peak hours. The station cost-reduction benefits associated with the tube trailer consolidation concept can be multiplied further in early FCEV markets, in which

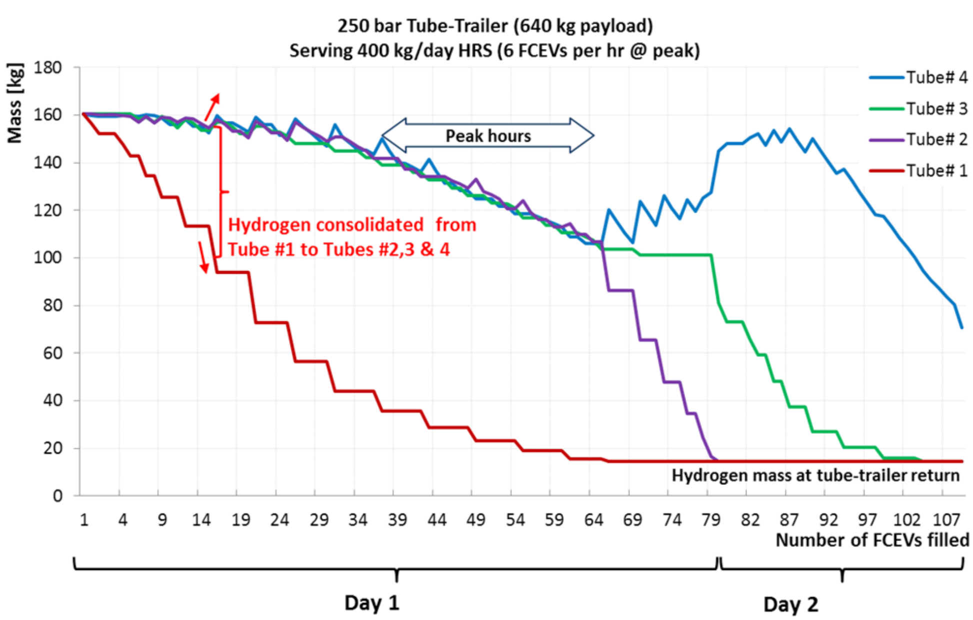

FIGURE 4. Status of Hydrogen Mass in Each of the Four Tube Trailer Vessels during Operation of the Refueling Station with the Consolidation Strategy

the cost of dispensed hydrogen is likely to be higher because underutilization of of the station equipment. The consolidation concept works in tandem with high-pressure tube trailer deliveries, which alone have the advantage of lowering the overall cost of compression by shifting a significant part of the process upstream to gas terminals; the economies of scale at terminals enable more efficient use of compression equipment than at the refueling station itself.

CONCLUSIONS AND FUTURE DIRECTIONS

By implementing consolidation strategy for managing hydrogen within tube-trailer vessels, the same station equipment can triple the station's capacity while satisfying peak demand with fast-fill rates (1.7 kg/min). For a given station capacity, the tube trailer consolidation strategy can reduce the compression cost at refueling sites by 60% and the total investment cost for refueling stations by 40%. Tube trailers with pressures higher than 250 bar (e.g., 350 bar and 500 bar) offer greater compression cost-reduction benefits with the consolidation strategy.

SPECIAL RECOGNITIONS AND AWARDS/PATENTS

Patent Application

1. Elgowainy, A., Reddi, K., "ENHANCED METHODS FOR OPERATING REFUELING STATION TUBETRAILERS TO REDUCE REFUELING COST", Docket No.: ANL-IN-13-058, submitted to United States Patent and Trademark Office on September 27th 2013.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. Reddi, K., Mintz, M., Elgowainy, A., Sutherland, E., "Challenges and opportunities of hydrogen delivery via pipeline, tube-trailer, Liquid tanker and methanation-natural gas grid", Wiley (in press).

2. Reddi, K., Elgowainy, A., Sutherland, E., 2014, "Hydrogen Refueling Station Compression and Storage Optimization with Tube Trailer Deliveries," Accepted for publication at the International Journal of Hydrogen Energy.

3. Reddi, K., Elgowainy, A., Sutherland, E., Joseck, F., 2014, "Tube-Trailer Consolidation Strategy for Reducing Hydrogen Refueling Station Costs," submitted for publication at the International Journal of Hydrogen Energy.