X.6 Analysis of Incremental Fueling Pressure Cost

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Project Start Date: October 2013
Project End Date: September 2014

Overall Objectives

Provide a platform for comparing impact of alternative refueling methods, fueling pressures, and pre-cooling temperatures on the refueling cost of hydrogen.

Fiscal Year (FY) 2014 Objectives

- Evaluate impact of fueling pressure on fill rate and refueling cost
- Incorporate implications of SAE International (SAE) J2601 refueling protocol in the modeling of hydrogen refueling stations (HRS)
- Identify cost drivers of various fueling technologies and configurations

Technical Barriers

This project directly addresses Technical Barriers A, D and E in the System Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. These barriers are:

(A) Future Market Behavior

(D) Insufficient Suite of Models and Tools

(E) Unplanned Studies and Analysis

Technical Targets

The project employs the Hydrogen Station Cost Optimization and Performance Evaluation (H2SCOPE) simulation tool to simulate the performance of the refueling system and to investigate the impact of fueling pressure and pre-cooling requirement on the fill time and refueling cost. The project examines the tradeoff between the fueling pressure (fill amount) and refueling cost for a target fill time of three minutes.

Contribution to Achievement of DOE System Analysis Milestones

This project contributes to achievement of the following DOE milestone from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Task 1.12: Complete an analysis of the hydrogen infrastructure and technical target progress for technology readiness. (4Q, 2015)
- Task 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)

FY 2014 Accomplishments

- A modeling framework (H2SCOPE) was developed to accurately evaluate various fueling pressures and pre-cooling temperatures.
- Evaluated the refueling times for various combinations of fueling pressures and pre-cooling temperatures.
- Evaluated the refueling costs for various combinations of fueling pressures, pre-cooling temperatures and station capacities.

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INTRODUCTION

Previous studies have indicated that the compression, refrigeration and storage combined, accounts for more than 75% of the refueling equipment cost. Additionally, refrigeration and compression are the two major components with significant operation costs. While the refueling station compression and storage requirements depend on the fueling pressure, the cooling requirement depends on the pre-cooling temperature. The pre-cooling temperature largely decides the fill rate for a given fueling pressure and initial vehicle tank condition. In this project we studied the impact of the combinations of different fueling pressures and pre-cooling temperatures on the refueling cost of hydrogen.

The H2SCOPE simulation model was developed from first principles by solving the physical laws subject to a set of initial and boundary conditions. H2SCOPE tracks the temperature, pressure and mass at all the points from the hydrogen source to the vehicle's tank within a refueling station. The model provided the opportunity of examining the highest fill rate possible with any combination of fueling pressure and pre-cooling temperature without exceeding the limits set by SAE J2601 protocol on pressure, temperature, and state of charge. The associated fueling costs were estimated for various combinations of fueling pressures and pre-cooling temperatures. The temperature rise inside the vehicle's tank is influenced by various parameters, including the tank's physical size and configuration, the tank thermal properties, and the initial conditions and boundary conditions of the tank system. The physical size, thermal properties, and initial conditions and boundary conditions of the fill process simulated by the H2SCOPE model are provided in Tables 1, 2 and 3, respectively.

TABLE 1. Vehicle Tank Characteristics

Tank Physical Properties	Fill Pressure (bar)		
	700	500	350
Capacity (kg)	5	4	3
Outer Diameter (inches)	19.5		
Thickness (inches)	1.83		
Tank Length (inches)	49.2		
Liner Thickness (inches)	0.2		
Volume (liters)	129		

TABLE 2. Vehicle Tank Thermal Properties

	Composite	Liner (Poly Ethylene)
Temperature Range (^{O}C)	-100 to 140	-100 to 140
Density (kg/m^3)	1,550	975
Specific Heat (J/kg-K)	500-1,500	1,000-3,000
Thermal Conductivity (W/m-K)	0.3-0.8	0.3-0.8
Thermal Diffusivity (cm^2/sec)	0.001-0.009	0.001-0.009

TABLE 3. Initial and Boundary Conditions of the Vehicle Tank System

Initial Pressure (bar)	20
Initial Temperature (Ambient, K)	298
Hot Soak Condition Temperature (K)	313
Maximum Pressure (bar)	875
Maximum Temperature (K)	358
Convective Heat Transfer Coefficient (W/m^{2}K)	325 (Inside), 5 (Outside)
Inlet (Dispensing) Temperature (K)	298, 273, 263, 253, 243, 233
Fill Strategy	Constant Pressure Ramp Rate

RESULTS

Figure 1 shows the minimum fill times possible for different fueling pressures at various pre-cooling temperatures while observing the limits specified by SAE J2601 fueling protocol. Figure 1 shows that for higher pre-cooling temperatures, the fueling pressures have greater impact on the fill duration. It also shows that the 700-bar refueling in Type IV tanks would require at least -30°C pre-cooling to fill 5 kg within 3 minutes. Additionally, pre-cooling to -20°C and -10°C is required to fill the vehicle's tank within 3 minutes for fueling pressures of 500 bar and 350 bar, respectively. Figure 2 shows the estimated refueling costs for filling the vehicle's tank at different fueling pressures within 3 minutes for a 750 kg/day station. It can be seen from the figure that partial fill of a vehicle's tank (i.e., with lower fueling pressures), significantly reduces the refueling cost. These lower fueling costs are due to the reduced cooling, compression and storage costs at refueling stations with lower fueling pressures. Although more dispensers are required to satisfy the demand for the 350-bar refueling to maintain the same refueling position availability for customers, the increase in dispenser cost does not negate

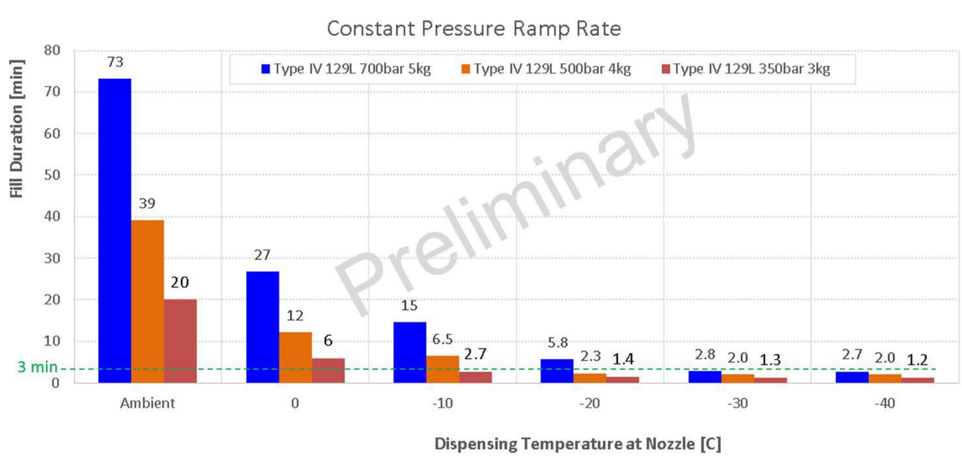


FIGURE 1. Estimated Fill Duration for Various Pre-Cooling Temperatures and Fueling Pressures

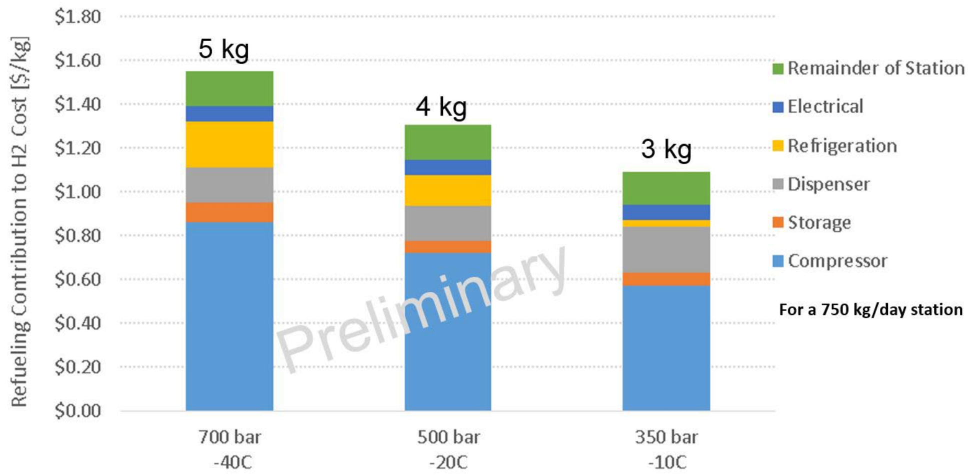
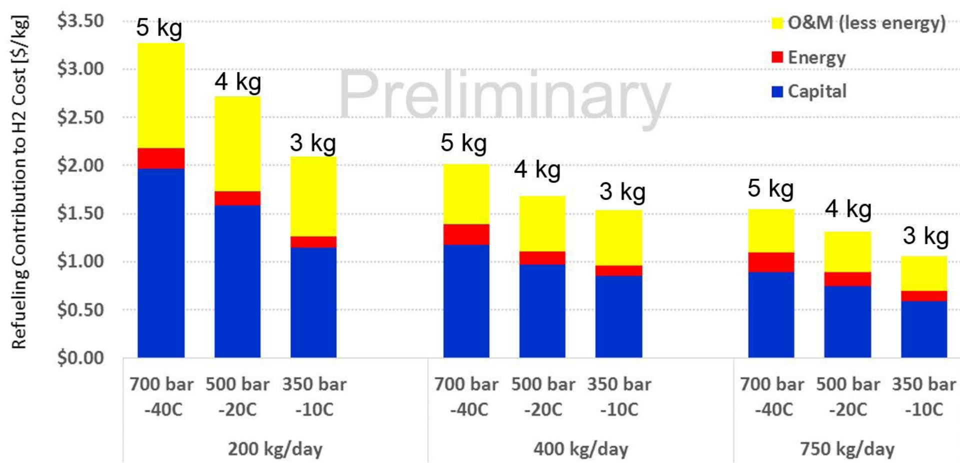


FIGURE 2. Estimated Refueling Cost by Component for Various Fueling Pressures at Same Fill Rate for a 750 kg/day Station



O&M - operations and maintenance

FIGURE 3. Estimated Refueling Cost for Various Fueling Pressures and Station Capacities for a Fill Time of Less Than 3 Minutes

the savings achieved from the reduction in the compression and storage and cooling costs. Figure 3 shows the refueling costs for station capacities of 200, 400 and 750 kg/day. The refueling cost savings with the lower fueling pressures is much greater for smaller station capacities compared to larger station. Greater cost savings would be realized in early fuel cell vehicle markets where the deployed stations are of small capacities and the utilization of such capacity is expected to be low with a slow initial vehicle deployment rate.

CONCLUSIONS AND FUTURE DIRECTIONS

The fueling pressure greatly impacts the fill duration, especially with higher pre-cooling temperatures. Filling the vehicle with lower pressures (partial fills) reduces the associated refueling costs. The reduction in refueling cost with lower fueling pressures is greater for lower station capacities and is primarily driven by the reduction is required compression, cooling and storage costs. In the future, the impact of station underutilization scenarios and the requirement of semi-continuous running of the pre-cooling equipment to satisfy the SAE J2601 time window need to be investigated to quantify the implication of various fueling pressures on refueling cost.

SPECIAL RECOGNITIONS & 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., "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.