III.12 Hydrogen Fueling Station Precooling Analysis

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Project Start Date: October 2014
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Evaluate the cost and energy consumption of precooling system at hydrogen refueling stations, and identify strategies for precooling cost and energy reduction

Fiscal Year (FY) 2015 Objectives

- Evaluate theoretical precooling requirement at hydrogen refueling stations (HRS) with respect to Society of Automotive Engineers (SAE) J2601 refueling protocol
- Determine size of precooling equipment and heat exchanger (HX) with various refueling demands and frequencies
- Assess current precooling equipment design and cost and identify major drivers for precooling cost and energy consumption
- Analyze tradeoff between different design concepts

Technical Barriers

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

(A) Future Market Behavior

(D) Insufficient Suite of Models and Tools

(E) Unplanned Studies and Analysis

Technical Targets

This project investigates the major drivers for precooling cost and energy consumption, including the impact of HRS utilization and frequency of fills, the impact of number of back-to-back fills, and the impact of SAE J2601 30-second window to reach precooling temperature.

Contribution to Achievement of DOE Systems Analysis Milestones

This project contributes to the following DOE milestone from the Systems Analysis section of the FCTO MYRDD 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 2015 Accomplishments

- Evaluated theoretical refrigeration capacity and precooling electricity consumption at hydrogen refueling stations (<1 kWh/kg$_{_H2}$)
- Developed a methodology to size precooling equipment and HX with respect to fill rate, number of back-to-back fills, and SAE J2601 30-second window
- Evaluated the tradeoff between on-demand cooling vs. large thermal mass heat HX
- Demonstrated the critical impact of HRS utilization on precooling energy consumption per kilogram of dispensed hydrogen
- Developed a formula for estimating cooling energy consumption kWh/kg$_{_H2}$

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INTRODUCTION

Reports from hydrogen refueling stations operating in Germany indicated that precooling electrical energy consumption exceeded 10 kWh/kg$_{_H2}$. Such energy consumption not only contributes more than \$1/kg$_{_H2}$ of operating cost, but also increases the greenhouse gas (GHG) emissions associated with hydrogen dispensing. Additionally, the precooling requirement at HRS to -40^{o}C within 30 seconds according to the SAE J2601 fueling protocol requires an oversized refrigeration capacity and/

or heat exchanger thermal mass, resulting in significant capital cost of the precooling system. The station's precooling requirements depend on many operational and demand variables, including precooling temperature, fill rate, and fueling frequency.

There are several precooling system designs and configurations employed by various companies at HRS around the world. The variation of implementation of precooling systems at HRS reflect the fairly new application of such systems to hydrogen refueling and the recent approval of the SAE J2601 protocol. This project evaluates the different refrigeration concepts and designs at existing HRS through theoretical calculations grounded in physical laws of thermodynamics and heat transfer.

RESULTS

We used the theoretical laws of thermodynamics to calculate the cooling energy requirement for -40°C precooling and calculated the corresponding electrical energy consumption based on estimates of refrigeration system coefficient of performance (COP) at different ambient temperatures. Figure 1 shows that at 35°C ambient, the energy required for cooling is approximately 0.3 kWh/$kg_{\_H2}$. The corresponding electricity consumption is estimated at 0.4 kWh/$kg_{\_H2}$ assuming a conservative precooling system COP of 0.8 at 35°C. Figure 2 shows the calculated mass of aluminum HX block for various temperature increase between refueling of hydrogen vehicles assuming 5 kg of hydrogen to be dispensed in each fueling. The mass of the HX is approximately 1,500 kg when allowing 4°C HX

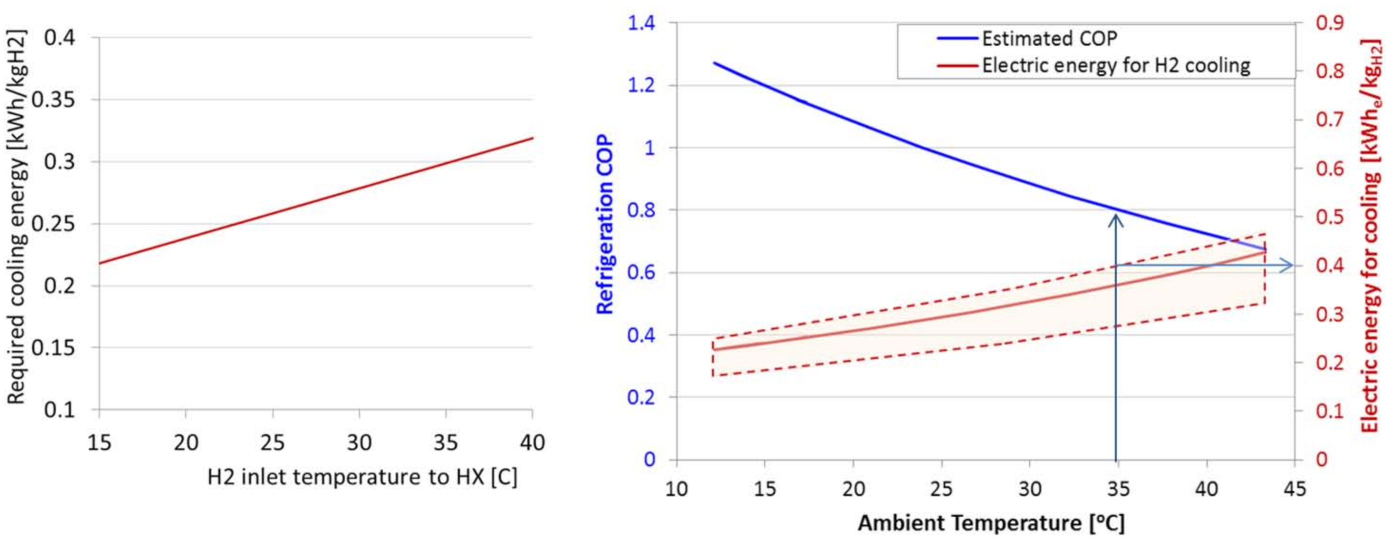

FIGURE 1. Cooling and electricity energy consumption at various ambient temperatures

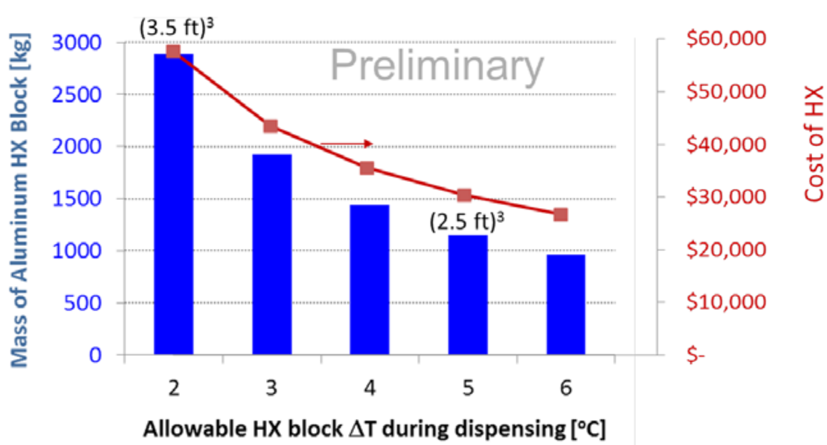

FIGURE 2. Impact of heat exchanger thermal mass on temperature change between fills

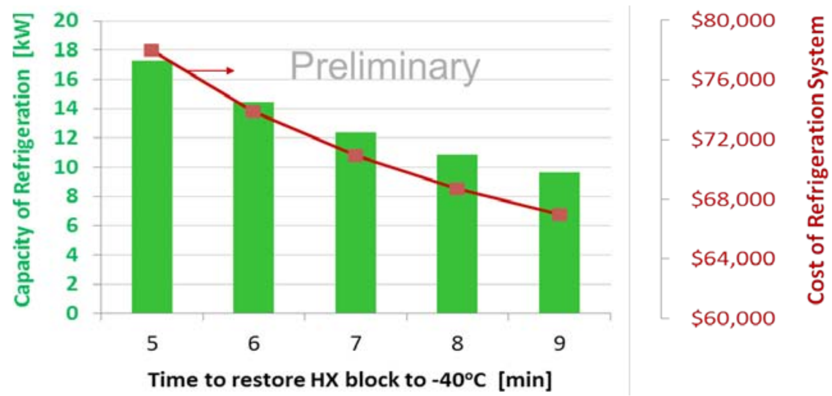

FIGURE 3. Refrigeration capacity requirement as a function of frequency of back-to-back fills

temperature rise with each fueling. A larger thermal mass of HX provides more reliable and near steady precooling at the dispenser during fueling.

Figure 3 shows the refrigeration capacity as a function of the time required to restore HX block to -40°C between back-to-back refueling. For a 5 $kg_{\_H2}$ fill in 5 minutes (+2 minutes lingering), a cooling capacity of 12 kW (3.5 ton) is required. The time required to restore HX block to -40°C is an important parameter to satisfy the design requirement of fill rate and number of back-to-back fills.

Argonne collected precooling energy consumption requirement from several hydrogen refueling stations in California. The collected data averaged 54 kWh of precooling electricity consumption per day at 25°C ambient with no refueling events. The 54 kWh represents the overhead energy consumption to keep the HX cold at -40°C all the time in anticipation of possible refueling demand at any time during the day. Argonne proposed the following formula to calculate the precooling electricity consumption per kilogram of hydrogen dispensed based on the aforementioned calculation of precooling energy consumption and the collected data of overhead electricity use.

$$\textit{Cooling Electricity Consumption}\ [kWh/kg_{H2}] \approx \frac{\left[0.3 + \frac{54}{\textit{Daily dispensed } kg_{H2}}\right]}{\textit{System COP}}$$

The formula shows that the precooling electricity consumption is a strong function of daily dispensed hydrogen. It is clear that when the average daily dispensed hydrogen is small (e.g., in the early phase of hydrogen vehicle deployment), the electricity consumption per kg of hydrogen can be significant as shown in Figure 4. The overhead electricity consumption diminishes in importance with average dispensed amount of greater than 100 kg/d.

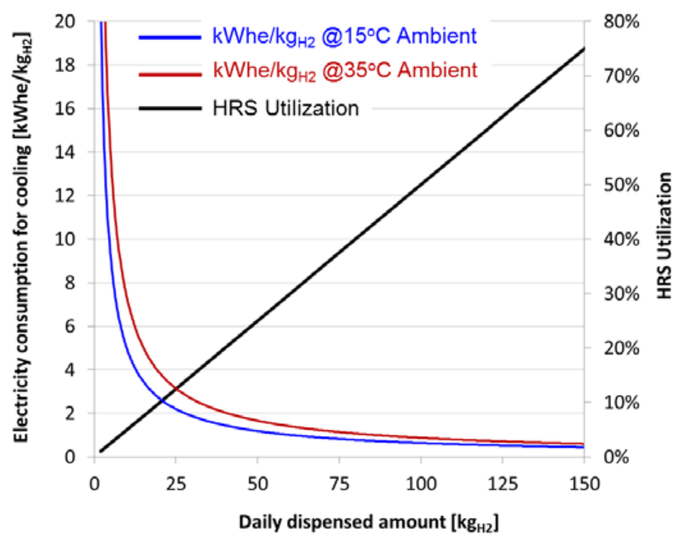

FIGURE 4. Electricity consumption for cooling H_2 as a function of refueling station utilization

CONCLUSIONS

The electrical energy required to precool the hydrogen at 35°C ambient is only about 0.3 kWh/$kg_{\_H2}$. However, modern-day stations additionally spend about 54 kWh keeping the heat exchanger at -40°C all day. The impact of this "overhead" on the levelized cost of hydrogen becomes significant when the daily dispensed amount is low, such as the case in early hydrogen vehicle markets. It is therefore important to report the daily dispensed amount along with the reporting of precooling electricity consumption per kg of dispensed hydrogen. When the daily demand of hydrogen exceeds 100 kg/d per hose, the precooling electricity consumption drops below 1 kWh/$kg_{\_H2}$.