III.13 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 system design strategies for minimizing the precooling cost and energy.

Fiscal Year (FY) 2016 Objectives

- Evaluate the available design strategies used for precooling at a hydrogen refueling station (HRS).
- Analyze tradeoff between different design concepts.
- Identify the impact of various refueling station parameters including back-to-back (B2B) fills, Joule–Thomson (J-T) expansion temperature rise, and hydrogen flow rate on precooling equipment and heat exchanger (HX) design and cost.

Technical Barriers

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

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

(I) Other Fueling Site/Terminal Operations

Technical Targets

This project investigates the major drivers for precooling cost and energy consumption, including the impact of frequency of fills, number of B2B fills, J-T temperature rise, and the hydrogen fill rate.

Contribution to Achievement of DOE Hydrogen Delivery Milestones

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

- Task 6.3: By 2020 reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <$2/gge of hydrogen for the gaseous deliver pathway. (4Q, 2020)

FY 2016 Accomplishments

- Acquired performance data at different ambient temperatures for a typical HRS precooling system.
- Developed an algorithm to optimize size of precooling equipment and HX for lowest precooling cost.
  - Evaluated the tradeoff between on-demand cooling vs. large thermal mass HX.
- Evaluated the impact of temperature increase due to J-T expansion and B2B fills.
- Evaluated energy consumption for precooling.

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INTRODUCTION

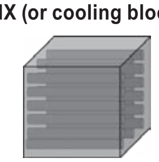
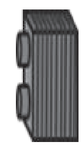
The cost of the precooling system per single dispensing position is currently in the range of $150,000–$200,000, representing approximately 10% of the total station capital cost. The SAE J2601 fueling protocol requires the HRS to achieve -40°C within 30 s from the start of fueling, which has led to oversized refrigeration capacity and/or HX thermal mass. Different precooling design concepts highlight the tradeoff between cost and other design constraints such as the physical size of equipment and the station's B2B fill capability. Reports from operating hydrogen refueling stations indicates that precooling electrical energy consumption is between 0.5–50 $kWh_e/kg\ H_2$. The different precooling design concepts and the wide range of reported electric consumption warrants a detailed modeling of precooling systems to understand the parameters that impact cost and energy consumption of precooling at HRS.

While the refueling station compression and storage requirements depend on the fueling pressure and demand profile, the cooling requirement depends on the hydrogen supply temperature and desired dispensing temperature, fill rate, fueling frequency or B2B fills, and performance requirements in the fueling protocol. 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 is mainly in the way energy from hydrogen is removed before dispensing, (1) through a large HX mass (cooling block) maintained at low temperature (below -40°C) by a refrigeration unit with relatively low cooling capacity or (2) through a small HX mass supported by a refrigeration unit with relatively high cooling capacity. This project evaluates the sizing of these components or combinations of these components through a cost optimization algorithm and using basic laws of thermodynamics and heat transfer. A comparison between two HX design concepts is presented in Table 1.

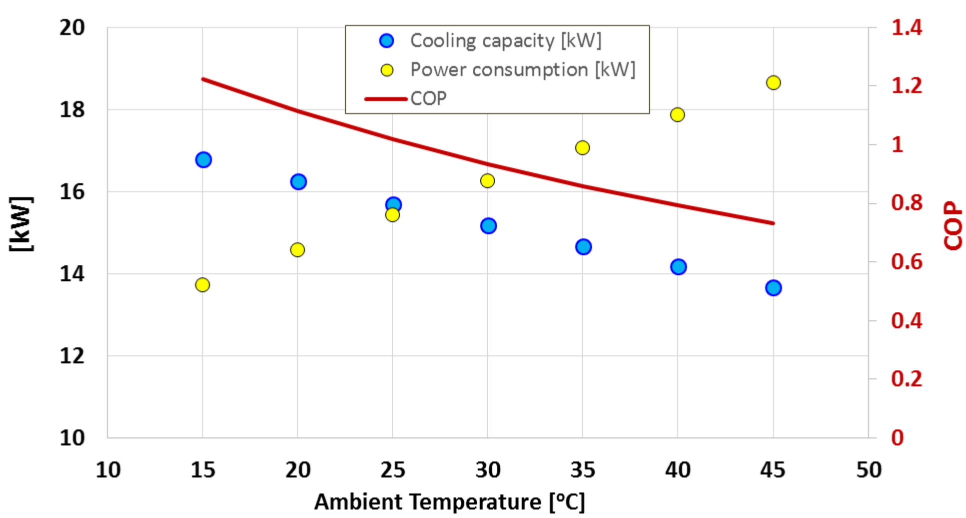
RESULTS

Basic laws of thermodynamics were used to calculate the cooling energy requirement for -40°C dispensing. The corresponding electrical energy consumption and cooling capacity were estimated based on reported performance of a typical refrigeration unit at different ambient temperatures. Figure 1 shows the impact of ambient temperature on the

TABLE 1. Comparison between the Considered HX Options

	Large thermal mass HX (or cooling block) 	**Compact thermal mass HX with high UA*** 
Physical size	Large mass and volume (typical block: about 1 ton, 27 ft^3)	Very small mass and volume (very high heat transfer area to volume ratio)
Cooling power requirement	Relatively small	Relatively large
Impact of ambient temperature on system cooling capacity	Less sensitive	More sensitive
Overhead cooling energy	Large (large thermal mass)	Small (very small thermal mass)
B2B fill capability	HX size increases with the number of B2B fills	Virtually infinite
Packaging/footprint	Large	Small (can fit inside dispenser cabinet)
Purchase cost	Low	High
Shipping and installation cost	High	Low

*UA – (U: overall heat transfer coefficient) x (A: heat exchange area)



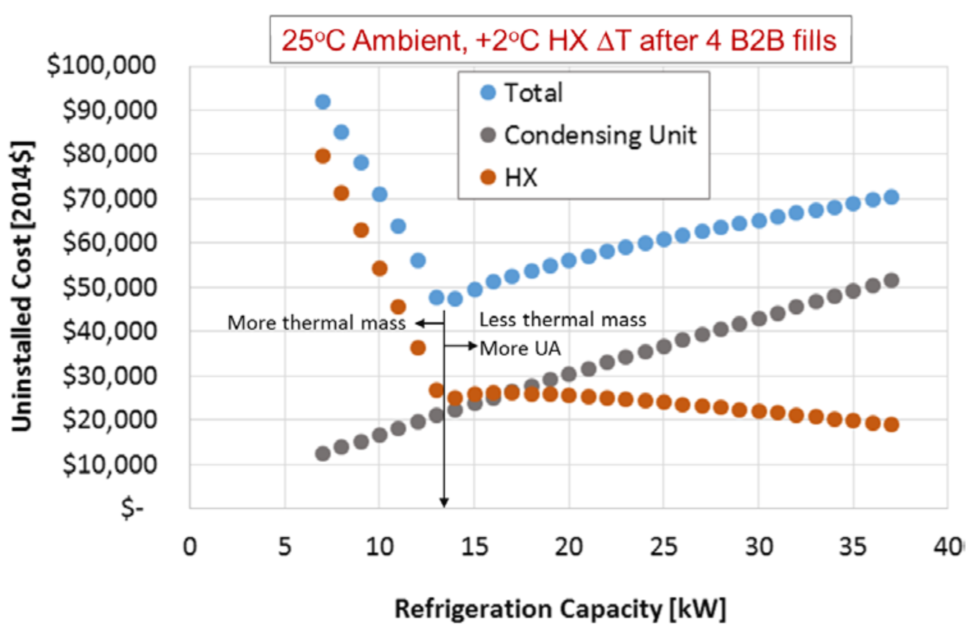
COP – Coefficient of performance

FIGURE 1. Performance of a typical precooling unit at an HRS at different ambient temperatures

performance a typical refrigeration unit at the HRS. With the increase of ambient temperature, the cooling capacity of the unit decreases while the power consumed increases. Figure 2 shows the total cost, condensing unit cost and HX cost of a precooling system required to support four B2B fills at an ambient temperature of 25°C while limiting the temperature rise of the HX unit to 2°C throughout the sequence of fills. An HX with large cooling block acts as a cooling buffer so that a low capacity condensing unit is required, while a small mass HX requires a high capacity condensing unit and large HX surface area. Considering the cost of the condensing unit and HX, an optimum combination of these two systems can be estimated for minimum cost, while meeting the design constraints of interest such as HX temperature rise, number of B2B fills and design point for ambient temperature. Figure 3 shows a typical HRS setup with a variable area control device (VACD) which controls the flow hydrogen between the high-pressure buffer storage and the HX of the precooling unit. During the refueling event, the pressure differential across the VACD valve results in a temperature rise due to J-T expansion across the VACD. Figure 3 also shows the temperature of hydrogen at the outlet of the VACD and inlet of the HX, indicating that hydrogen may reach the HX at a higher temperature compared to the ambient, which represents an added load on the precooling system. Figure 4 shows the electric energy consumption of a typical precooling unit measured at a refueling station with the daily ambient temperature varying between a low of 10°C and a high of 18°C. The figure shows a daily overhead electric energy consumption (to keep the HX cold) of approximately 10 kWh at these ambient temperatures. Such daily electric energy should be amortized over the entire daily dispensed amount, and then added to the electricity consumption for cooling the hydrogen (approximately 0.3 kWh/kg H_2) to estimate the total precooling electric energy consumption per kilogram of dispensed hydrogen.

CONCLUSIONS

When sizing the precooling unit components (condensing unit and HX) to satisfy a specific performance target (e.g., -40°C and number of B2B fills), there is an optimum combination of the precooling system components for a minimum total cost. The temperature rise due to J-T effects across the VACD is significant and should be taken into account while designing the station layout. It may be favorable to cool the hydrogen using an ambient HX upstream of the precooling system.



ΔT – Change in temperature

FIGURE 2. Cost of various precooling system design concepts (four B2B fills at an ambient temperature of 25°C with HX temperature rise limited to 2°C)

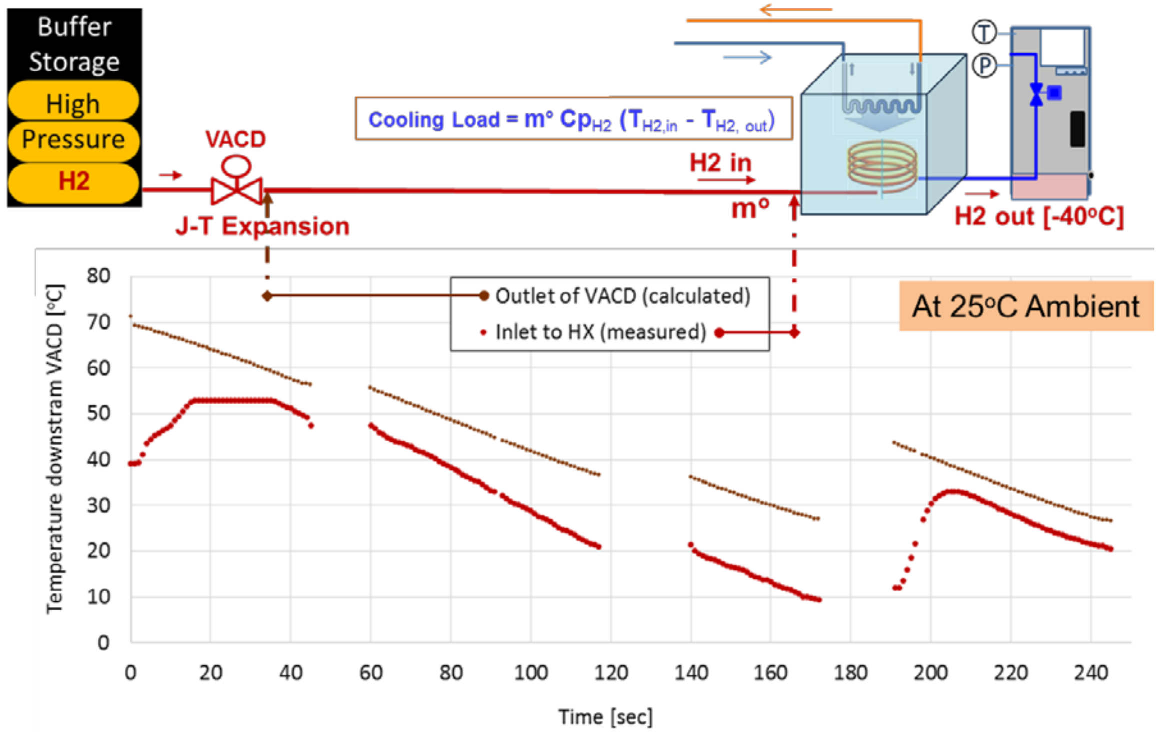


FIGURE 3. Hydrogen temperature variation downstream of the VACD during a typical refueling event

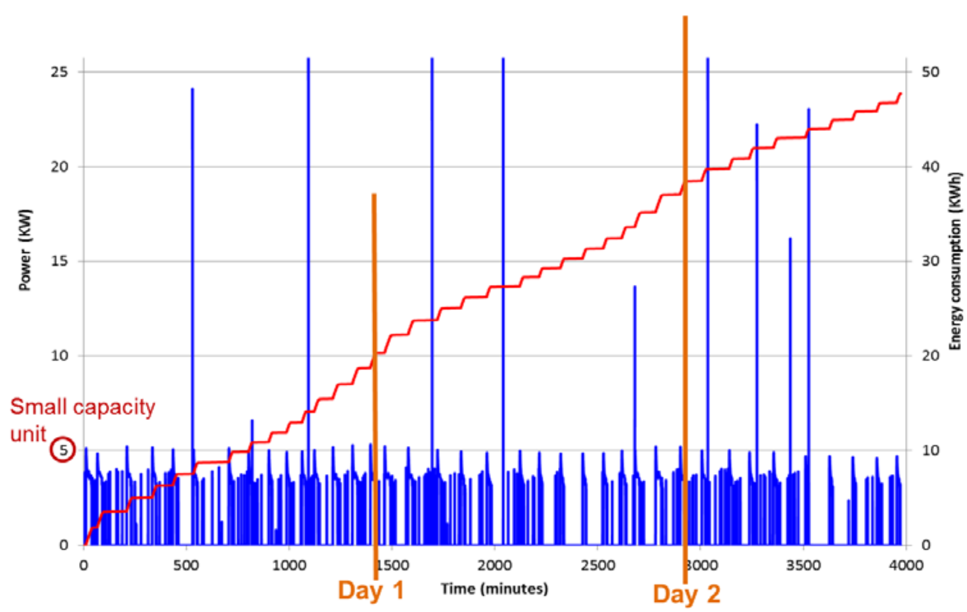


FIGURE 4. Electric energy consumption by precooling system during a typical station daily operation (daily ambient temperature varying between a low of 10°C and a high of 18°C)