Hydrogen Fueling Station Pre-Cooling Analysis

Amgad Elgowainy and Krishna Reddi
Argonne National Laboratory

June 9, 2016
**Overview**

**Timeline**
- Start: FY 2016
- End: Determined by DOE
- % complete (FY16): 60%

**Budget**
- FY15 Funding: $100K
- FY16 Funding: $100K
- 100% DOE funding

**Barriers/Challenges**
- Lack of hydrogen infrastructure options analysis
- Cost and efficiency of delivery components
- Lack of appropriate models and analytical capability
- Conduct unplanned studies and analyses

**Partners/Collaborators**
- NREL, PNNL
- Cal. State Univ. LA
- Boyd Hydrogen
- Honda R&D Americas, Inc.
- Hydrogen station operators
Precooling is a major contributor to refueling cost – Relevance/Motivation

- Equipment cost of refrigeration unit plus heat exchanger (HX) is significant
  - $100K - $200K per hose

- Wide range of electric energy for cooling is reported
  - 0.5 – 50 kWh_{e}/kg_{H2}

- State of the technology is not well understood
  - Emerging system designs and different implementation practices
  - Challenges with meeting sequential back-to-back (BB) fills at HRS
Identify major drivers for precooling capacity/cost and performance – Approach

- **Collaborate** to acquire information on cost and performance of various precooling design configurations
- **Evaluate** current precooling design concepts at hydrogen refueling stations (HRS)
  - Analyze trade-off between various design concepts
- **Identify** major drivers for precooling capacity/cost and performance
  - Impact of number of back-to-back (B2B) fills
  - Impact of J-T expansion on inlet temperature to HX
- **Develop** precooling system optimization algorithm for various component costs and performance specifications (e.g., # of B2B fills)
- **Analyze** trade-off between different design concepts
- **Vet** analysis results and findings
  - Internally via partners
  - Externally, via collaborators, interaction with US DRIVE Tech Teams, and reaching out to experts from industry
Acquired information on a typical refrigeration system used in HRS – Approach

Low temperature (-40°C) precooling requires complex refrigeration cycle and system design.
Acquired performance data at different ambient temperatures for a typical HRS precooling system – Accomplishment

> Strong impact of ambient temperature on precooling performance
Updated precooler cost formula – Accomplishment

- $20K for 15 kW cooling capacity
- Installation factor = 2 : 2.3
Developed an algorithm to optimize size of precooling equipment and heat exchanger for lowest precooling cost – **Accomplishment**

- Optimizing HX size for desired # of B2B fills can reduce refrigeration capacity requirement.
- Sizing for cooling on-demand is more expensive option.
  - especially if using compact HX for compact packaging.

**25°C Ambient, +2°C HX ΔT after 4 B2B fills**

- Cooling on-demand: large UA, no thermal mass (buffer) needed.

---

[Image of graph showing cost vs. refrigeration capacity, indicating the trade-offs between thermal mass and UA for different levels of precooling efficiency.]
## Trade-off between two different HX design concepts

<table>
<thead>
<tr>
<th></th>
<th>Large thermal mass HX (cooling block)</th>
<th>Compact, high UA, HX</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical Size</strong></td>
<td>Large mass and volume</td>
<td>Very small mass and volume</td>
</tr>
<tr>
<td>(typical block is ~1 ton, 27 ft³)</td>
<td></td>
<td>(Very high H.T. area/volume ratio)</td>
</tr>
<tr>
<td><strong>Cooling power</strong></td>
<td>Relatively small power requirement</td>
<td>Relatively large power requirement</td>
</tr>
<tr>
<td><strong>Sensitivity to ambient</strong></td>
<td>System cooling capacity is less</td>
<td>System cooling capacity is more</td>
</tr>
<tr>
<td></td>
<td>sensitive to ambient temperature</td>
<td>sensitive to ambient temperature</td>
</tr>
<tr>
<td><strong>Cooling energy overhead</strong></td>
<td>Large cooling overhead (large thermal mass)</td>
<td>Small cooling overhead (very small thermal mass)</td>
</tr>
<tr>
<td><strong>B2B Fill Capability</strong></td>
<td>HX size increases with # of B2B fills</td>
<td>Virtually infinite</td>
</tr>
<tr>
<td><strong>Packaging/footprint</strong></td>
<td>Large footprint</td>
<td>Small, can fit inside dispenser cabinet</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>- Purchase cost is low</td>
<td>- Purchase cost is high</td>
</tr>
<tr>
<td></td>
<td>- Shipping and installation cost is high</td>
<td>- Shipping and installation cost is low</td>
</tr>
</tbody>
</table>
More stringent requirement on B2B fills or allowable block temperature rise increases precooling system capacity and cost – Accomplishment
Improper sizing of refrigeration system can jeopardize HRS ability to perform B2B fills

- With respect to # of B2B fill capability

**Chiller Performance 21 March 2016**

- Full Recovery
  - 5.9 kWh
  - 58.9 min
  - 6.46 kW_{max}

- B2B Recovery
  - 3.7 kWh
  - **45 min**
  - 6.46 kW_{max}

**Dispenser Performance 21 March 2016**

- Fill Data
  - 4.36 kg
  - 3.8 min
  - 20 g/s_{avg}

Credit: Danny Terlip, NREL
$H_2$ inlet temperature to HX and mass flow rate define cooling load and HX size

Cooling Load = $m^o \cdot C_{pH2} \cdot (T_{H2, in} - T_{H2, out})$

- Several HRS operators reported significant increase in heat exchanger temperature during initial period of fill.
Temperature increase due to J-T expansion increases precooler system capacity and cost – Accomplishment

- J-T temperature increase must be mitigated before inlet to precooler HX
  - Locate VACD far upstream of HX to allow for thermal energy dissipation
  - Install low-cost ambient HX between VACD and precooler HX
Precooling system cost is estimated to drop by 25% with volume production of HX – Accomplishment

─ Needed to estimate potential for cost reduction of current HX technology with mass production

Preliminary

$\Delta T$ after 4 B2B fills

$25^\circ C$ Ambient, $+2^\circ C$ HX
Precooling energy per kg$_{H2}$ for each fill is small ~0.3 kWh/kg$_{H2}$ – Accomplishment

- At COP 0.8-1.0, precooling electric energy use during fill is 0.3-0.4 kWh$_e$/kg$_{H2}$
- Overhead cooling electric energy consumption to keep HX cold is in the range of 20-60 kWh$_e$/day
Examined current pre-cooling system design, operation, and performance at four different HRS

Updated precooling system components costs

Developed an algorithm to optimize size of precooling equipment and heat exchanger for lowest cost

- Impact of number of back-to-back fills
- Impact of J-T temperature rise across VACD
- On-demand cooling (high UA) vs. large thermal mass HX

Identified major factors impacting precooling system performance and cost

- Optimizing HX size for desired # of B2B fills can reduce precooling system capacity and cost
- Cooling on-demand is more expensive compared to buffering with large thermal mass HX
- J-T temperature increase must be mitigated before inlet to precooler HX
  - Locate VACD far upstream of HX to allow for thermal energy dissipation
  - Install low-cost ambient HX between VACD and precooler HX

Evaluated and compared calculated precooling energy use during each fill with field performance data (~0.3-0.4 kWhₑ/kg₇)
Collaborations and Acknowledgments

Collaborators and Partners:

– PNNL: Daryl Brown provided cost of refrigeration and heat exchanger equipment
– NREL: Danny Terlip shared performance data on precooling equipment at NREL
– Cal. State Univ. LA: Prof. David Blekhman shared precooling performance data for T20 HRS
– Boyd Hydrogen: Bob Boyd provided specific cost and performance data on precooling equipment
– Honda R&D Americas, Inc.: Steve Mathison shared data on precooling equipment performance from Honda’s T40 HRS
Future Work

- Evaluate trade-off between other precooling design concepts
  - various HX designs (brine-based thermal HX, compact HX, etc)
  - with respect to cost, footprint, B2B fill capability, installation cost, sensitivity to ambient temperature, and temperature increase through VACD

- Quantitatively examine implications of VACD location with respect to J-T temperature rise through modeling and measurements

- Update Hydrogen Delivery Scenario Analysis Model (HDSAM) and Hydrogen Refueling Station Analysis Model (HRSAM) with:
  - updated precooling cost and design options
  - Include optimization algorithm for proper sizing of precooling equipment with desired refueling performance attributes (e.g., # of B2B fills)

- Continue to collaborate with partners to acquire information on cost and performance of alternative precooler design concepts

- Review and publish updated models and analysis results
Project Summary

- **Relevance:** Equipment cost of pre-cooler at HRS is significant ($100K-$200K per hose). Evaluate cost and performance of emerging system designs and implementation practices. Examine implication of various precooling design concepts on energy consumption per kg of dispensed hydrogen.

- **Approach:** Collaborate to acquire information on cost and performance of various precooler design configurations. Evaluate current precooling design concepts at HRS. Analyze trade-off between various design concepts. Identify major drivers for precooling capacity/cost and performance. Develop precooling system optimization algorithm for various component costs and performance specifications. Analyze trade-off between different precooling design concepts.

- **Collaborations:** Collaborated with experts from national laboratories and industry to examine current precooling equipment design and cost. Acquired operation and performance information needed for modeling and simulations, and received valuable input to complete /review modeling results and analysis.

- **Technical accomplishments and progress:**
  - Updated precooler system components costs, and developed an algorithm to optimize size of precooling equipment and heat exchanger.
  - Identified major factors impacting precooling system performance and cost (e.g., # of B2B fills and temperature rise through VACD).
  - Evaluated and compared calculated precooling energy use during each fill with field data.

- **Future Research:** Evaluate trade-off between other design concepts of HX designs. Quantitatively examine various implications of VACD location through modeling and measurement. Update Hydrogen Delivery Scenario Analysis Model (HDSAM) with updated precooling cost and design options. Review and publish updated models and analysis results.