III.7 Compressor-Less Hydrogen Refueling Station Using Thermal Compression

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Overall Objectives

- Demonstrate the technical and economic feasibility of the thermal compression concept for compressor-less hydrogen refueling stations.
- Quantify the total station costs, both capital and operating, to determine if a thermal compression station can achieve a hydrogen levelized cost reduction of 15% when compared to a conventional liquid hydrogen (LH2) refueling station.

Fiscal Year (FY) 2016 Objectives

- Develop a transient simulation model to capture the thermodynamics of the thermal compression station.
- Optimize a preliminary full scale station design using outputs from the transient simulation model.
- Research and determine the most cost-effective high pressure cryogenic vessel (HPCV) design suitable for use in the thermal compression station.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

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

(B) Reliability and Costs of Gaseous Hydrogen Compression

Technical Targets

This project is a feasibility study which will identify the potential advantages of a thermal compression station versus a conventional LH2 refueling station. Because this station will not use a hydrogen compressor, this project addresses all of the DOE targets for small compressors specifically:

- Availability: >90%
- Uninstalled Capital Costs: $170,000
- Annual Maintenance: 2%

The thermal compression station will not require refrigeration equipment upstream of the gas dispenser, so this project will also address refrigeration equipment target:

- Uninstalled Capital Cost: $70,000

FY 2016 Accomplishments

- Completed a transient thermodynamic model capturing the physics of the thermal compression fueling station.
- Showed how the model could be used to optimize the size and quantity of HPCVs required for a 400 kg/d station.
- Showed how the model could be used to analyze the effects of eleven physical and operational station variables to study their impact on the amount of hydrogen boil-off losses that occur during the process.
- Developed a process flow diagram showing the major equipment needed for a 400 kg/d thermal compression station.
- Initiated research into the type of materials and designs of HPCVs suitable for the thermal compression cycles.

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INTRODUCTION

The thermal compression refueling station concept utilizes the thermomechanical exergy of LH2 to create the pressure necessary for 700 bar dispensing. In this station, LH2 delivered to onsite LH2 dewars will be used to fill custom designed HPCVs. The liquid hydrogen will then be heated at constant volume allowing the pressure to build within the HPCV to the necessary 800–900 bar dispensing pressure. A thermal compression refueling station utilizing a series of HPCVs will be designed and optimized to satisfy the hydrogen fueling demand of a mid-sized refueling station (400 kg/d).

The goal of this project is to assess the technical and economic feasibility of thermal compression for cost effective high-pressure (700 bar) hydrogen refueling stations. This concept has the potential to reduce fueling station costs by eliminating expensive and maintenance-prone compressors. The target station size for this project is 400 kg/d, and with this size station, 15% reductions in capital and operational costs (hydrogen levelized) when compared to traditional LH2 refueling stations are to be demonstrated.

APPROACH

The approach that will be used to demonstrate this conceptual station consists of two major steps. The first step is to optimize the design of the station in terms of equipment and utilization of the LH2 delivered to the station. This step is achieved by developing a rigorous transient thermodynamic model of the station that allows multiple physical and operational variables to be investigated for their impact on station design. The model will be used to optimize the size and quantity of HPCVs and identify station parameters that will minimize the hydrogen boil-off that occurs during the process. The second step of the approach is to evaluate the design options for the HPCVs. A study is being conducted of existing pressure vessel designs as well as some innovative alternatives. This study will conclude with a list of potential HPCV designs which will be evaluated for economic impact on the station.

The thermodynamic modeling and the HPCV evaluation will define the major equipment needed for a thermal compression station. This station design will be compared to a traditional LH2 refueling station using Argonne National Laboratory's Hydrogen Delivery Scenario Analysis Model assumptions and economic analysis. If the thermal compression station shows a 15% reduction in hydrogen levelized cost, the project can move forward to the next phase. The second phase of the project will be to build a small scale test loop to demonstrate key aspects of the thermal compression process, such as pressurization and dispensing rates.

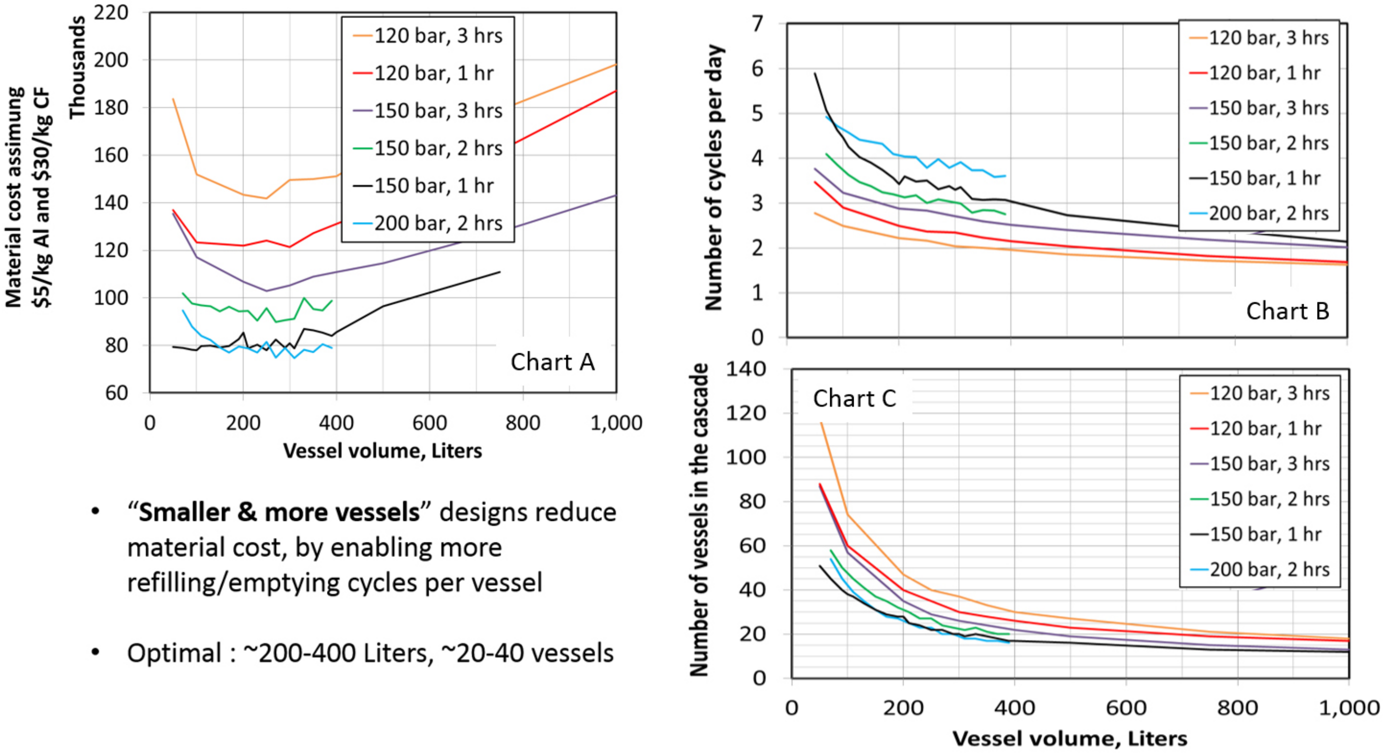
RESULTS

In May of 2016 the thermodynamic simulation modeling of the thermal compression station was completed. Two Fortran subroutines were written. The first subroutine modeled the operation of the fueling station in order to determine how many HPCVs are needed to satisfy station demand. Inputs to the subroutine include variables such as vehicle fueling profile, vehicle capacity, number of dispenser hoses in use, and HPCV volume. The charts in Figure 1 show how the model can be used to investigate the influence of station variables on the required number of HPCVs. The results shown in Figure 1 are for a Type III vessel with an aluminum liner and carbon fiber wrapping. Note that this analysis will be repeated and refined later in the project when a better understanding of the HPCV design is achieved. A material cost can be applied to each cylinder volume. Chart A of Figure 1 shows a relationship between the overall cost of HPCV materials for the station versus the HPCV volume. This type of analysis lead to the conclusion that a larger quantity of smaller HPCVs would be more cost effective that fewer larger HPCVs.

The second thermodynamic simulation subroutine focused on quantifying the amount of hydrogen boil-off that occurs during the thermal compression process. The thermal compression process involves the transfer of LH2 to the HPCVs and recycling of gaseous hydrogen from the HPCVs back to the LH2 dewar. The boil-off subroutine was used to investigate eleven key station variables to determine how these variables influence the amount of hydrogen that is stranded during the hydrogen transfers. Thousands of model runs were conducted in order to try to identify which variables have the largest impact on the amount of hydrogen vented. The results of the modeling were quite scattered and machine learning techniques such as Sobol indices were used to help understand sensitivities.

This second subroutine was also used to investigate the overall process flow, especially the recycling of hydrogen back to the LH2 dewar from the HPCVs. The model was run to determine the differences between returning the hydrogen to the top or bottom of the dewar. Figure 2 shows that bottom return is the preferred location because top return results in excessively high LH2 dewar pressures. The subroutine was then used to analyze the thermal flows in the process. As a result, the thermal compression process steps were re-evaluated and two new flow strategies were conceived to minimize the amount of hydrogen losses. The first strategy, "topping off," uses warm stranded gas in one of the HPCV vessels to pressure equalize with a vessel that has just been filled with LH2. The second strategy, "pre-cooling," utilizes the cold gas that is a product of flashing LH2 during the HPCV filling process to pre-cool the next vessel in line to be filled with LH2. The boil-off subroutine was modified to incorporate bottom return and these two new process steps and the impact on the reduction in boil-off was significantly improved as can be seen in Table 1.

A mid-sized, 400 kg/d, station capacity was targeted for a detailed design. Other station parameters such as



- "**Smaller & more vessels**" designs reduce material cost, by enabling more refilling/emptying cycles per vessel
- Optimal : ~200-400 Liters, ~20-40 vessels

FIGURE 1. Influence of switch pressure, time off-line and vessel volume on overall material cost, number of cycles per vessel and number of vessels in the cascade, assuming a Type III pressure vessel design

Top return:

- Very important pressure rise
- BUT lowest liquid temperature (20 K) , thus higher density, thus colder vessel in filling step, thus virtually no boil-off during filling of HPCVs
- Recycle step sensitive

Bottom return:

- Moderate pressure rise (<100 psi), low pressure at low mass in Dewar
- BUT higher liquid temperature, thus more boil-off during HPCV filling
- HPCV filling step sensitive

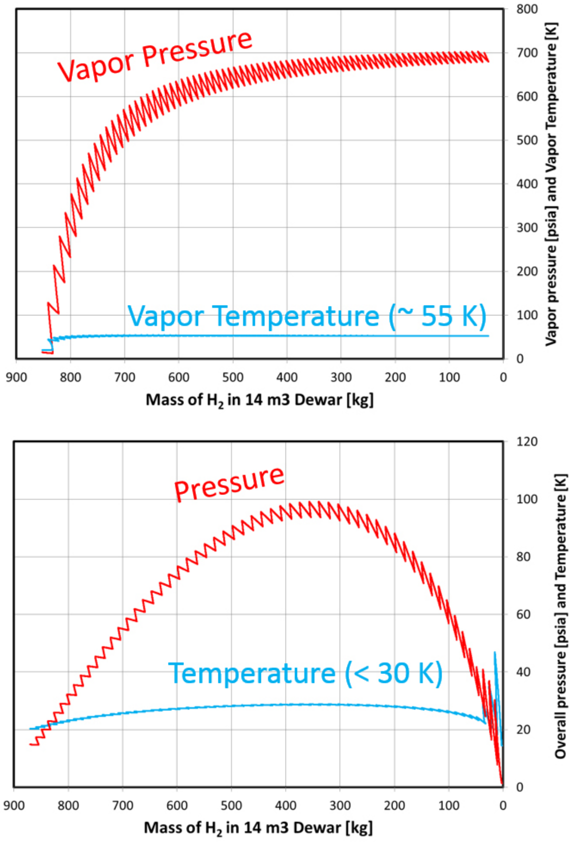


FIGURE 2. Pressures and temperature in LH2 dewar for top versus bottom return

TABLE 1. Impact of Pre-Cooling and Topping-Off on Total Hydrogen Boil-Off, Assuming LH2 Initially at 20.3 K in the Dewar and 110 bar Switch Pressure

Case #	Initial LH2 in Dewar (kg)	Dewar Volume (m^3)	Topping-Off	Pre-Cooling	Extra Cooling During Filling	Max Dewar Pressure (psia)	Boil-Off Total (% of kg delivered)
1	900	14	No	No	No	100	77
2	900	14	Yes	No	No	87	44
3	900	14	Yes	Yes	No	100	20
4	900	14	Yes	Yes	Yes	105	11
5	900	20	Yes	Yes	Yes	85	9
6	900	25	Yes	Yes	Yes	75	8.5
7	600	14	Yes	Yes	Yes	85	9
8	400	14	Yes	Yes	Yes	67	7.5

fueling profile, number of dispenser hoses, and the amount of hydrogen delivered to each vehicle were also locked in as station constants. Using these inputs and some known properties of Type III vessels, the model determined that 20–30 HPCVs with a volume of 200–300 L would likely be a near-optimum station design. The final station design is dependent on the HPCV design study, so these results will be refined at the completion of that study. A preliminary process flow diagram has been created assuming a station size of 30 HPCV of 250 L internal volume. A snapshot of this drawing is shown in Figure 3. The equipment identified in this drawing will be accounted for in the economic analysis of the thermal compression station.

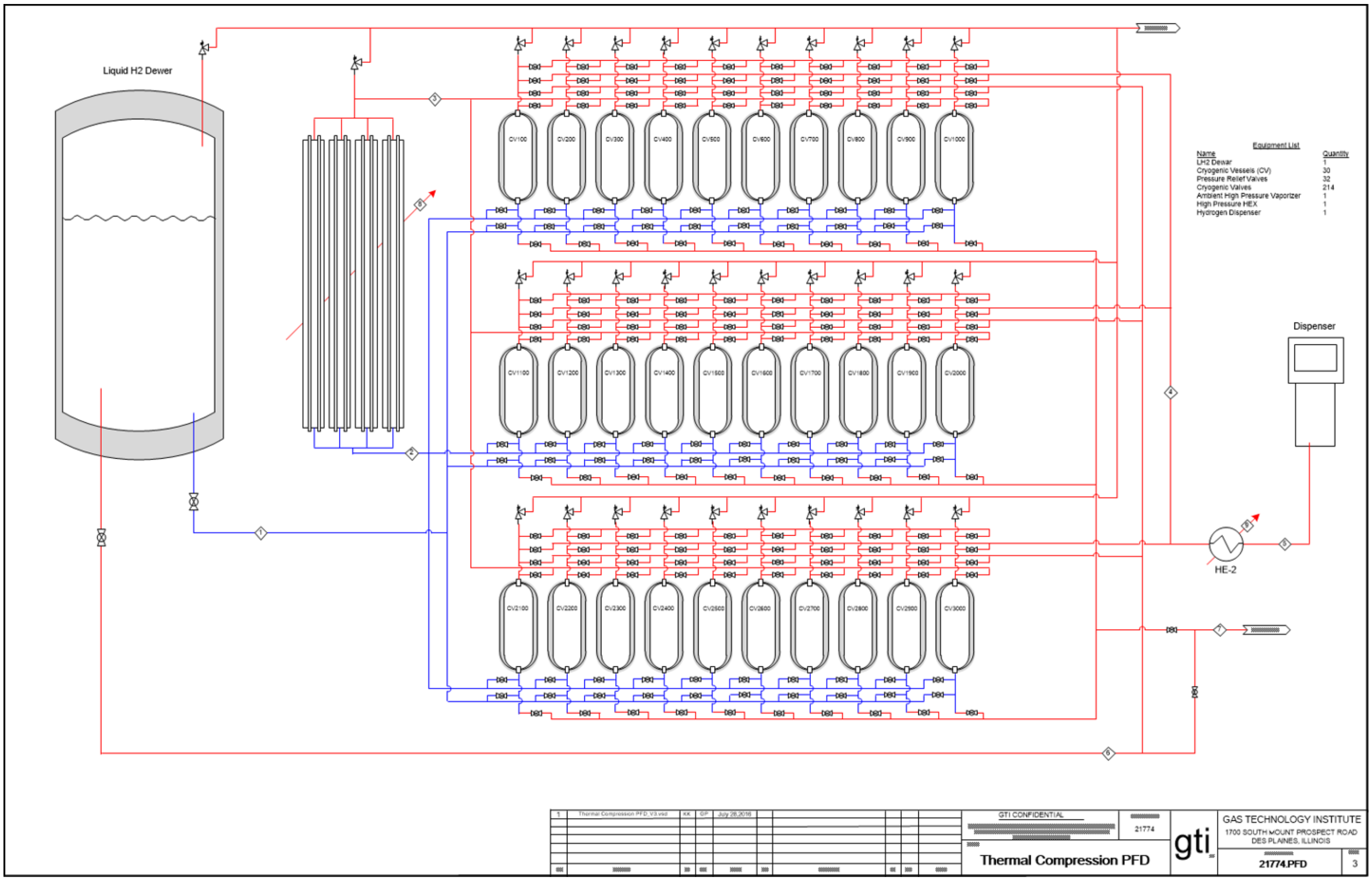


FIGURE 3. Preliminary process flow diagram of the thermal compression fueling station concept

The evaluation of HPCVs is due to be completed in early November of 2016. The HPCV must be able to withstand the following cycle conditions:

1 bar @ 20 K → 900 bar @ 160 K (3–5 cycles per day)

To date most of the research has been focused on Type I, all metal, pressure vessels. Type I vessels can be designed and fabricated according to the American Society of Mechanical Engineers code rules. While there is cryogenic data and hydrogen compatibility data available for some common metals, such as stainless steel 316, data is very limited for less popular metals that may have a cost advantage over stainless steel. Lower cost metals as well as other pressure vessel types will continue to be evaluated with the understanding that additional testing will be required to collect necessary data on the performance of these materials at the thermal compression cycle conditions.

CONCLUSIONS AND FUTURE DIRECTIONS

Based on the work conducted throughout the year several conclusions can be drawn.

- The thermodynamic simulation modeling of the thermal compression station has proven to be a useful tool both in providing input for station design as well as identifying processes steps that required improvements in order to make this concept viable.
- Modeling work shows that a larger number of smaller vessels has economic advantages over a smaller number of larger cylinders.
- The larger number of cylinders and the need for pre-cooling and top-off steps has increased the complexity of the station. The station’s valve count has increased which will have a greater impact on the overall station cost than originally expected.
- The availability of HPCVs suitable for the extreme temperature and pressure is very limited.

Future Work includes:

- Completion of HPCV evaluation.
- Economic comparison between thermal compression station and conventional LH2 station.
- Small scale demonstration if a 15% cost reduction for thermal compression station over conventional station can be shown.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Copyright for Thermal Compression Station Simulation (TCSS). Version 1.0 issued 04/20/2014, limited distribution, OCEC-16-064, LLNL-CODE-689637.