Innovating Hydrogen Station: Heavy-Duty Fueling

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National Renewable Energy Laboratory
WBS #8.6.2.1
6/6/2022

DOE Hydrogen Program
2022 Annual Merit Review and Peer Evaluation Meeting

Project ID: H2061

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Project Goal

A research and industry partnership for an experimentally validated high flow rate fueling model and near-term hydrogen station innovations

- First-of-its-kind, experimental research capability for 10 kg/min, 60+ kg fueling at 70 MPa and -40°C.
- Comprehensive high flow rate fueling models validated with experimental data.
- Publicly available tools and data for the benefit of hydrogen station stakeholders.

Three Key Aspects

Experimental Data

Computational Fluid Dynamics

Simplified Fluid Model H2FillS

Overview

Timeline and Budget

- Project start date: 8/1/2019
- Project end date: 9/30/2022
- Total CRADA budget: $2.8M
  - Recipient share: $1.4M
  - DOE share: $1.4M
  - Total spent*: $2.8M
    * As of 04/01/2022
- Related Projects Funded by HFTO:
  - HD Vehicle Simulator: $384k
  - EU PRHYDE Participation: $330k
  - DOE Site Readiness: $392K

Partners

- Shaun Onorato (PI, NREL)
- Co-PI(s): Dr. Taichi Kuroki, Daniel Leighton, Joshua Martin,& Matthew Ruple
- Partner organization(s)
  - Air Liquide – Industry Energy
  - Honda – Industry OEM
  - Shell – Industry Energy
  - Toyota – Industry OEM

Relevance/Potential Impact

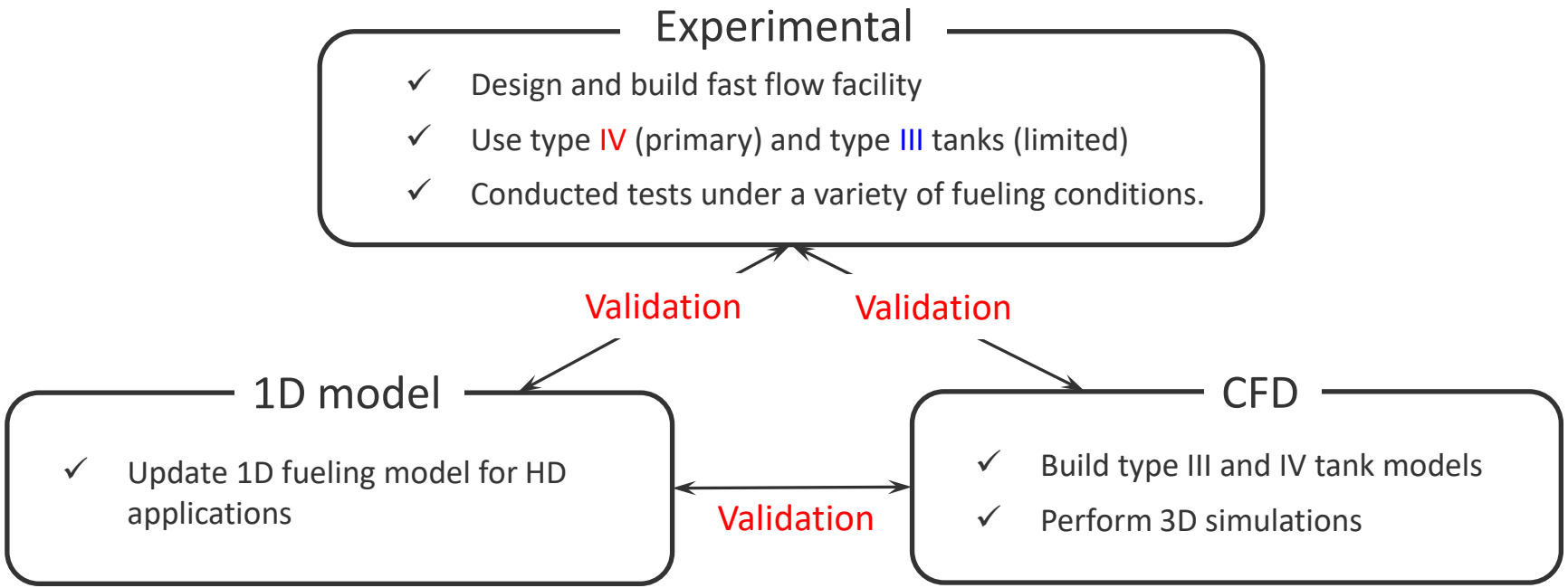
- This project addresses technological gaps for medium and/or heavy-duty fuel cell electric truck storage systems in terms of high flow rate fueling data, high flow rate system models, and light duty station/component reliability.
- Establishes first-of-its-kind **research and modeling capabilities** to drive medium and heavy-duty hydrogen fueling protocols and hardware development.
- Addresses the viability of DOE Hydrogen Class 8 Long Haul Truck Targets.
- Relevant to DOE goals specifically in the areas of:
  - lowering greenhouse gas emissions and criteria pollutants for medium/heavy-duty vehicles
  - building clean energy infrastructure
  - providing pathways to private sector uptake
- This project will generate critical experimental data and publicly available modeling tools for the benefit of all stakeholders and leverage industry/lab partnerships for future research needs.

Approach

- Upgrade NREL's legacy station to achieve HD fast fills at mass flow rates of 10 kg/min average (20 kg/min peak) at 70 MPa at -40°C.
  - Meet DOE Hydrogen Class 8 Long Haul Truck Targets (10/31/2019).
- Develop high flow rate fueling models that build on legacy tools (H2FIllS) and NREL's high performance computing capabilities (CFD modeling).
- Execute a comprehensive test program that utilizes a flexible HD vehicle simulator with multiple configurable tanks and temperature conditioning.
  - Compare fast vs slow fill gaseous hydrogen fueling.
- Collect fast flow data for model validation and dissemination to stakeholders to drive industry innovation.
- Compile lessons learned in design and commissioning.

NREL's Hydrogen Station in Golden, Colorado

Approach

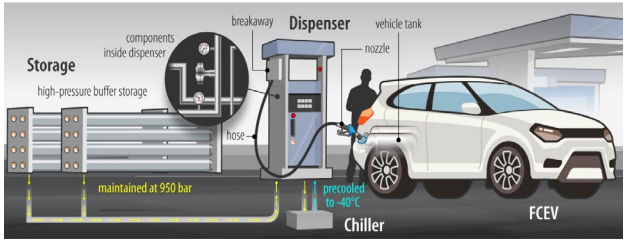


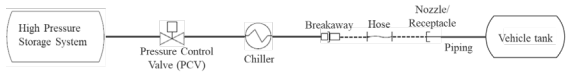
CFD simulations and experiments are conducted to make the 1D model reliable.

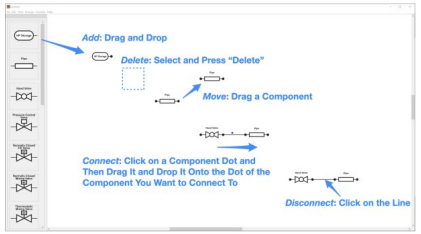
Approach

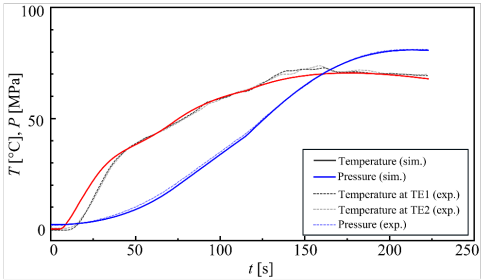
HD Hydrogen Filling Simulation (H2FIllS)

- H2FIllS is an 1D physics-based thermal fluid model that simulates the real-world fueling process from the high-pressure storage system though vehicle storage tanks.
- H2FillS allows evaluation of the changes in the temperature, pressure, and mass of components during the fueling process. It also evaluates the interaction between the station and vehicle (how significantly the pre-cooling temperature impacts the temperature rise inside the vehicle tanks).
- The MD/HD version was created based on the modified publicly available LD version https://www.nrel.gov/hydrogen/h2fills.html.









Advantage of H2FillS

- Helps user(s) understand how individual components influence the fueling performance, which helps station operators & vehicle OEMs optimize their station and vehicle designs.

Disadvantage of H2FillS

- H2FillS cannot simulate the temperature distributions within components (i.e. inside vehicle storage tanks). Computational fluid dynamics (CFD) is needed.

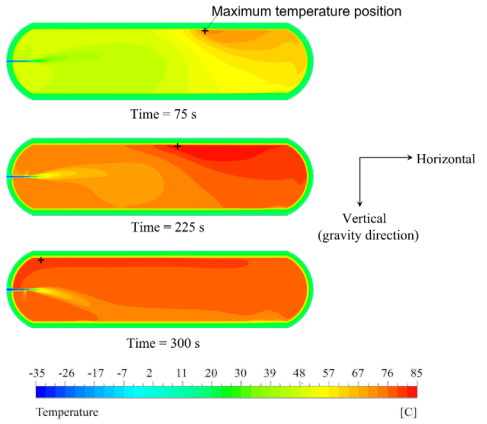
Approach

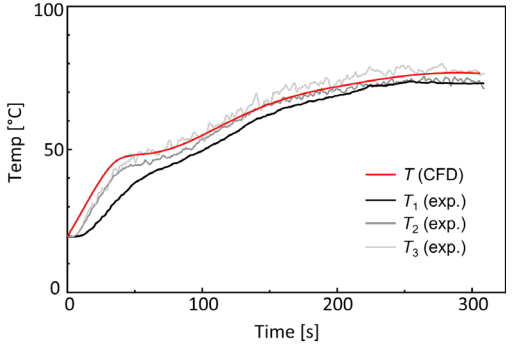
Computational Fluid Dynamics (CFD)

- CFD involves 3D physics-based modeling that simulates thermal and flow fields inside/outside components.
  - This makes up for H2FIllS' disadvantages in 1D.
- CFD tank modeling allows the evaluation of:
  - CHSS geometries impacts on thermal and flow fields.
  - Significance of temperature gradients.
- CFD leverages NREL's High Performance Computing (HPC) supercomputer which allows:
  - Different tank sizes to be modeled.
  - Multiple simulations per tank.
  - Different tank injector investigations (straight, angled, etc.).

- Models are continuously validated against experimental data and H2FillS.

High Performance Computing (HPC) System



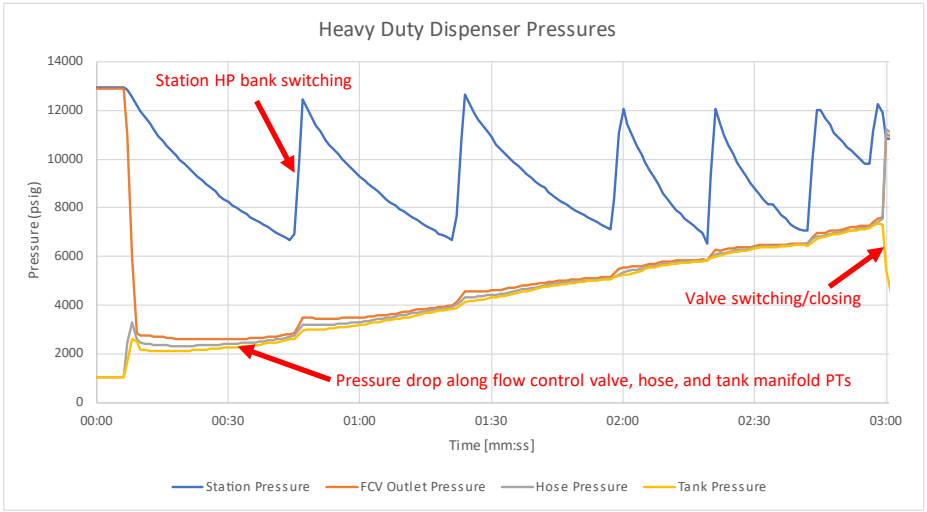


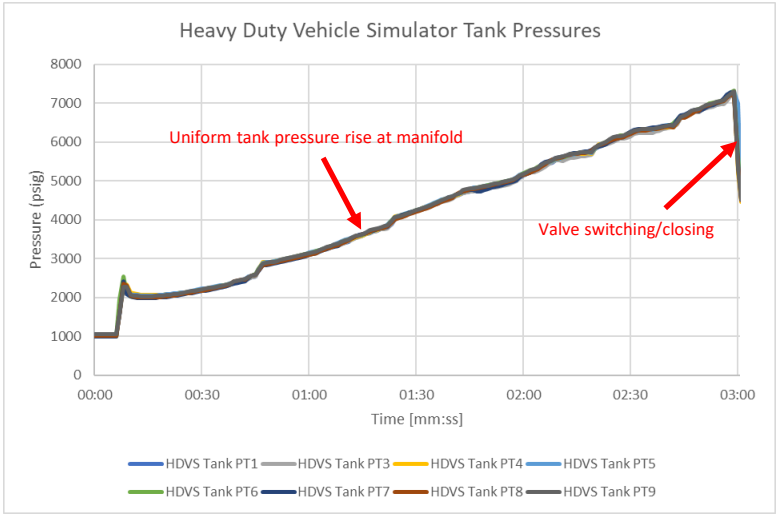
Example CFD Simulation Results

Accomplishments and Progress

Major Fast Flow Milestone Completed on 4/26/2022!

- Milestone Language: Complete systems installation and demonstrate H2 fueling at 70MPa supply, 10 kg/min average, 20 kg/min peak, and 35+ kg fill mass.
- Completed: 40.3 kg fill into the HDVS in 2.87 minutes at 14kg/min average and 21 kg/min peak.
  - Pressure ramp rate of 11.8 MPA/min
  - Starting pressure 1000 psi to 7200 psi (max 50 MPa for Phase II testing and increased to 70 MPa for Phase III)
  - 500 psi switching pressure, station HP storage tanks at ~13,000 psig



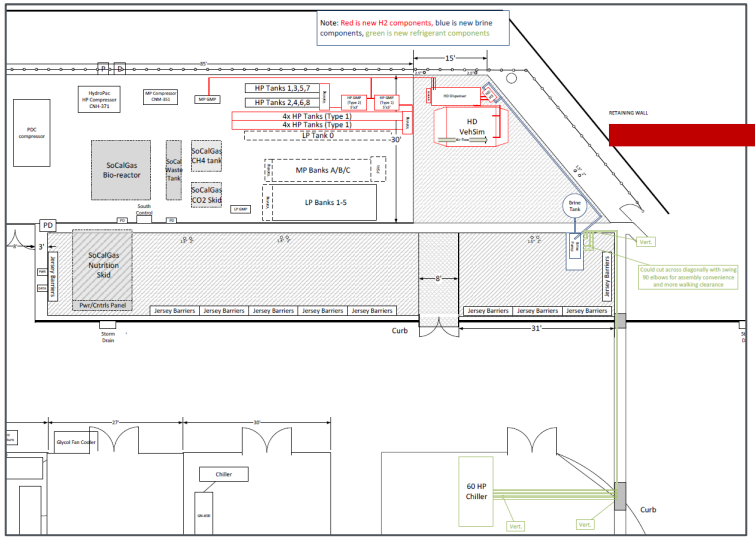


Accomplishments and Progress

Significant progress made on the HD station over the last year.

<u>All systems installed, operating, and station commissioning underway with preliminary testing.</u>

- HD Station comprised of expanded bulk hydrogen storage (gaseous), new gas management panel, brine-based chiller/precooling system, heavy-duty dispenser, and heavy-duty vehicle simulator.



NREL's HD Station in Golden, Colorado

Accomplishments and Progress

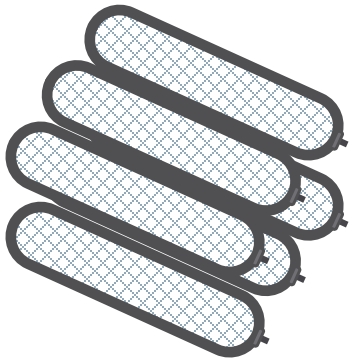
HD Station Commissioning Progress

- Currently engaged in flow control valve characterization and preliminary flow tests in HD vehicle simulator.
- Bank switching control strategies are being evaluated and refined.
- Major station controls and safety systems are implemented and functioning.
    - Working through bug fixes, additional programming, and troubleshooting during flow tests.
- Chiller/pre-cooling systems are commissioned and operating with automated controls.
    - Brine tank at -40°C and maintaining thermal stability.
    - expected heat exchanger performance including pressure drop.

Accomplishments and Progress

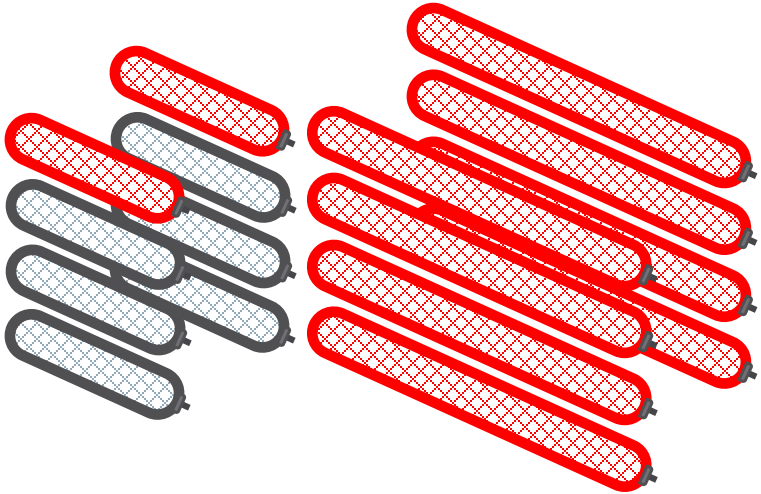
- High-pressure Ground Storage for a Single HD Fill

MP Storage



13.5 kg each x 6
81 kilograms total

HP Storage



16 kg each x 8
128 kilograms total

32 kg each x 8
256 kilograms total

*Existing vs. New Storage

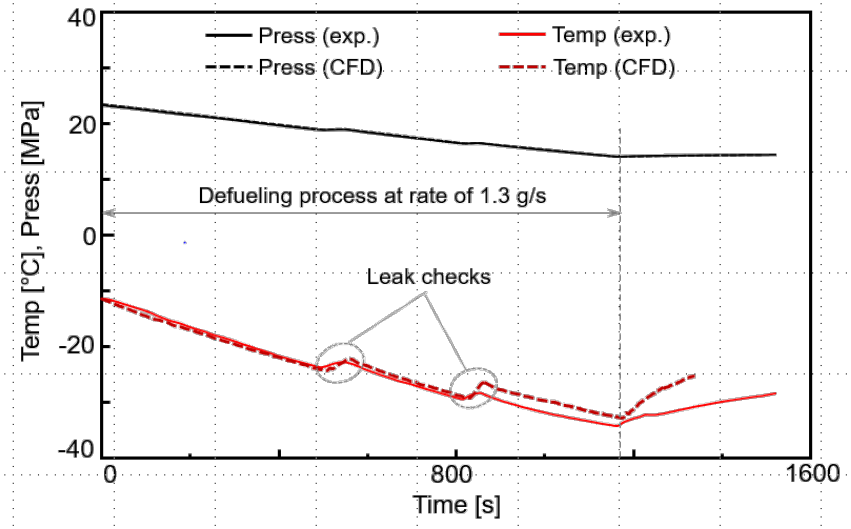
NREL HD Station

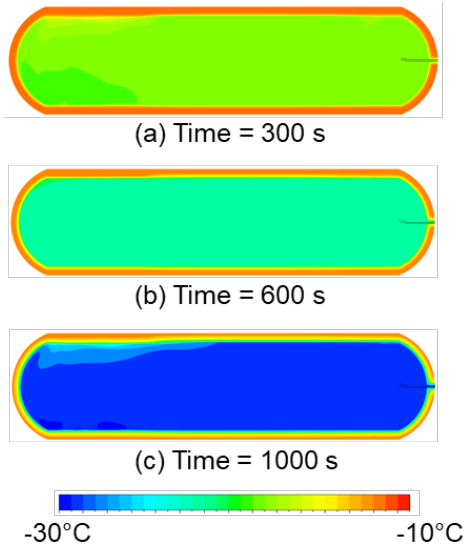
- 665 kg of bulk gas storage
- Cascade approach
- NREL modeling shows that at +60 kilograms GH2 transfer at ~10 kg/min average flow rate the hydrogen required at :
- **~80 kilograms at 40 MPa**
- **~380 kilograms at 90 MPa**

Station is not capable of back-to-back filling at +60 kgs .

Accomplishments and Progress

3D CFD Modeling Work





- Defueling CFD simulations were performed under the same conditions as observed in HD station experiments.
  - The CFD simulation results show only a few Kelvin difference from the experimental data.
  - It appears the temperature field might be uniform within the tanks during the defueling process.

Accomplishments and Progress

1D Modeling Work HD-H2FillS Upgrades

Modeling work with H2FillS:

- NREL's HD station was built in H2FillS.
- The HD station specific configuration was utilized for the support of station commissioning.
  - Flow control valve characterization and flow rate/pressure ramp rate thresholds.
- Data generated confirms if the model accurately predicts gas temperatures and pressures at sensor locations within the HD station.

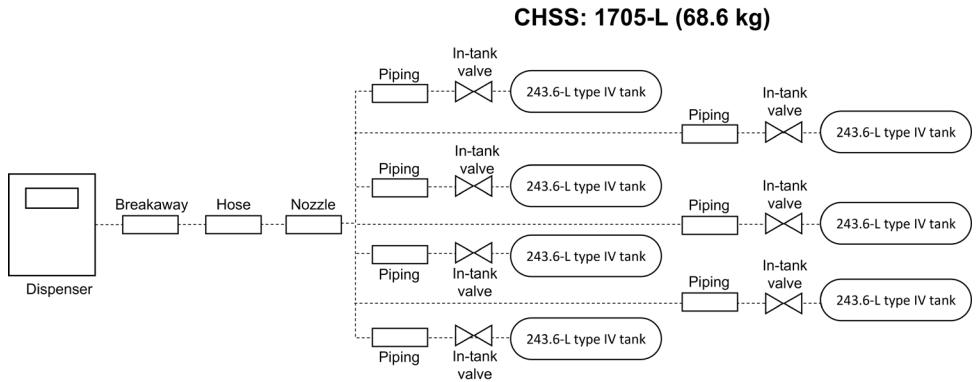


Fig. Modeled NREL's HD station

Note that medium pressure piping is used in the model to mimic the breakaway, hose, and nozzle.

Accomplishments and Progress

1D Modeling Work with EU PRHYDE Project and other DOE funded efforts:

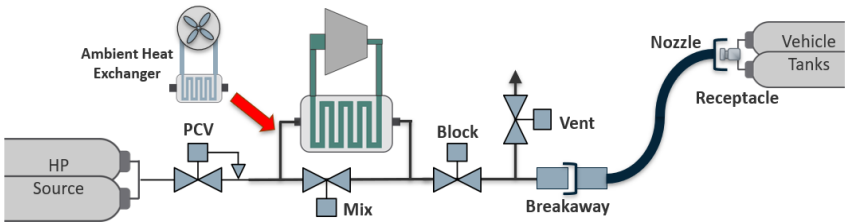
- Demonstrated that the H2FillS model has the same capability and reliability as the PRHYDE model.
- The NREL team has modified the H2FillS model so that it can be used in the project by adding a CHSS temperature throttle function.
- Working with PRHYDE to run simulations that assist in developing the fueling tables for the candidate fueling protocols.
    - The protocols will be evaluated at the NREL HD station under the new HD Fueling Methods project along with industry provided fueling hardware.
- Models built for DOE funded Electricore Heavy-Duty Dispenser and Nozzle project.
    - Dispenser and hardware will be tested at NREL's HD station and models validated based on data generated.

MOU link: https://www.ccjdigital.com/stakeholders-form-group-to-develop-test-hydrogen-fueling-hardware-for-hd-trucks/
DOE link: https://www.energy.gov/nepa/downloads/cx-101809-high-pressure-high-flow-rate-dispenser-and-nozzle-assembly-heavy-duty

Accomplishments and Progress

Innovating Hydrogen Stations – Light Duty

- Experimentally quantify the performance of an ambient precooling system to reject heat to the environment and reduce the energy and capacity required for hydrogen precooling thermal systems.



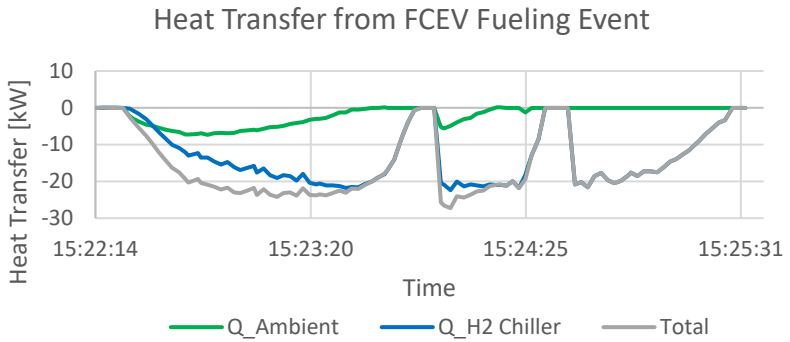
Generalized Hydrogen Dispenser Flow Path

- Diffusion-bonded, microchannel heat exchanger installed on commercial dispenser at ESIF.
- System activates when the outlet temperature of the hydrogen from the pressure control valve is above the inlet temperature of the glycol coolant to the heat exchanger.

Heat Exchanger, Valves, & Instrumentation Location

Accomplishments and Progress

Innovating Hydrogen Stations – Light Duty



	Peak Heat Transfer [kW]	Total Fill Heat Transfer [kJ]
H2 Chiller	-22.3	-2626.6
Total	-27.3	-3025.2
Savings	18.0%	13.2%

Heat exchanger efficiency is over 90%

System Performance For Initial Fueling Events

Fill #	Starting SOC	Peak Shaving	Fill Savings	Glycol Inlet Temp Avg [C]	Ambient Temp Avg [C]
1	11.7%	17.5%	9.8%	6.6	7.9
2	19.3%	18.0%	13.2%	-3.5	-2.8
3	36.3%	9.8%	10.4%	15.37	13.4
4	15.4%	9.2%	11.7%	-2.7	-9.4

Range of conditions to test:

- Starting vehicle SOCs
- Ambient conditions (CHSS tanks & glycol coolant)
- Back-to-Back fueling into HyVS
- System active during entire fill (installation & operation simplicity)

Accomplishments and Progress

Major project deliverables and milestones:

Focus Area	Deliverables	Status
High Throughput Fueling Systems Development and Integration	Experimental setup and design review for high throughput LD and HD fueling performance	Complete
	HD high flow rate buildout	Complete
	Complete systems installation and demonstrate: - H2 fueling at 70MPa supply, 10 kg/min average, 20 kg/min peak, and 35+ kg fill mass	Complete
	Collect experimental data for varying vehicle tank starting pressure, ambient temperature, delivered mass, and fuel temperature. Targeted flow rates 10 kg/min average, 20 kg/min peak, target fill amount 60-100 kg.	In Progress
	Alternate Tank Type: Collect experimental data for varying vehicle tank starting pressure, ambient temperature, delivered mass, and fuel temperature. Targeted flow rates 10 kg/min average, 20 kg/min peak, target fill amount 60-100 kg.	In Progress
Heavy-Duty Fueling Model	Develop and validate high flow rate tank CFD model	In Progress
	Develop high flow rate fueling thermodynamic model	Complete
	Validate high flow rate fueling thermodynamic model	In Progress
	Deliver publicly available, validated high flow rate fueling model	In Progress
Light-Duty Infrastructure Advancements	Collect experimental data for multi-dispenser LD high throughput fueling and provide analysis for performance and cost reduction opportunities for> 1,000 kg/day stations	Complete
	Cost Reductions: Ambient temperature precooling for J-T heat rejection	Complete
	LD CFD Modeling	Complete

Future Work

HD Station:

- Collect performance data for moving to Phase III of full flow testing.
  - Collect experimental data for varying vehicle tank starting pressures, ambient temperatures, delivered masses, and fuel temperatures. Targeted flow rates 10 kg/min average, 20 kg/min peak, target fill amount 60-100 kg.
  - Continue preliminary flow control tests and full system characterization
- Continue to refine controls and software for process control.
  - FCV, bulk gas storage bank switching, valves, pre-cooling, etc.
- Conduct full flow tests at 10 kg/min average, 20 kg/min peak, target fill amount 60-100 kg.
- Report test data and modeling validation to stakeholders and public.

Modeling:

- Validate H2FillS and CFD modeling against fueling data collected during ongoing flow tests.
- Align HD station and HDVS testing with partners and international partners (DOE/PRHYDE/NEDO)
- Release new version of HD-H2FillS for public use.

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

- The timeline is the only identifiable and significant concern; however, it appears that this project has simply been affected by the COVID-19 pandemic, like many other projects and the global economy in general. If the project does end up time-constrained, DOE should find some way to provide flexibility for the project's completion date.

Significant delays were experienced due to COVID-19 and global supply chain shortages. The project requested a no cost time extension to 9/30/2022 (approved by DOE and partners) to ensure that the project work can be executed. The project made significant strides during the spring of 2022 meeting the first major flow rate milestone and is on track to meet other major milestones within May 2022.

- It would be good to see more information on how a developer of HDV fueling protocols and equipment can access the resources that the project is putting in place, especially with regard to support for modeling and validation.

NREL is participating in the EU PRHYDE project as a technical expert, the primary industry driver for international HD protocols development. Modeling capabilities and data generated during the project will be made available to the PRHYDE group as well as to the public for protocols development. The new HD-H2FIllS model will be made publicly available after validated with experimental data generated at the NREL HD Station (expected fall 2022).

- As mentioned in the presentation, HDV nozzle, hose, breakaway, and receptacle standards and hardware are under development and should be considered for integration into the project as soon as possible, as those elements will play a significant part in the safety and reliability aspects of HDV fueling infrastructure and there are many lessons to be learned by including them in both the hardware and modeling elements of the project.

Building on the success of this project, NREL will evaluate newly developed HDV nozzles, hoses, breakaways, and receptacles under DOE FOA and CRADA projects. An industry supplied HD dispenser will also be evaluated at the NREL HD Station as part of the DOE FOA project.

- If any progress is made on protocol development within the timeframe of this project, the team should run some tests and incorporate them into the model. That being said, it might be a given with the level of coordination within the industry.

NREL will evaluate the EU PRHYDE developed protocols under the new HD Fueling Methods Project along with associated industry supplied HDV nozzles, hoses, breakaways, and receptacles.

Collaboration and Coordination

- **Industry:** Air Liquide, Honda, Shell, Toyota
  - Monthly updates on progress
  - Provide feedback on technical approach
- **International Japan:** Kyushu University
  - Continued collaboration on H2FillS
- **International EU:** IHS team joined EU PRHYDE project as a technical expert
  - Received additional funding from HFTO to participate
  - Dedicated test days with NREL's hardware system, multiple tank data is of value to the group

Source: https://prhyde.eu/

PRHYDE is a European based project, funded by the FCH2 JU under the Horizon 2020 program, looking at the current and future developments needed for refueling medium and heavy-duty hydrogen vehicles, predominantly road vehicles, but also other applications such as rail and maritime.

Remaining Challenges and Barriers

- Finalize commissioning of the new HD station and vehicle simulator.
  - Refine controls and safeties based on fast flow testing.
  - Implement additional sensors (pressure and temperature).
- Supply chain challenges due to COVID-19.
- Receive final approval to operate flow tests at full pressure (70 MPa) to meet .

Proposed Future Work

- HD station and project work will enable testing of new heavy-duty fueling protocols, dispensers, and nozzle hardware under DOE/industry funded work.
  - Electricore Heavy-Duty Dispenser and Nozzle Project (FOA)
  - Assessment of HD Fueling Methods (Industry lead CRADA)
  - Other future efforts

Summary

Goals:

- Demonstration of first-of-its-kind, experimental research capability for 10 kg/min, 60+ kg fueling
- Comprehensive high flow rate fueling models validated with experimental data (HD-H2FIllS & CFD)
- Publicly available tools and data for the benefit of hydrogen station stakeholders for the development of HD fueling protocols and hardware.

Progress:

- Major fast flow milestone completed on 4/26/2022 with a 40.3 kg fill into the HDVS in 2.87 minutes at 14kg/min average and 21 kg/min peak and -40°C.
- Ongoing Computational Fluid Dynamic fills have been completed on NREL's HPC and compared to experimental data with good correlation.
- H2FillS is in being upgraded for HD applications including improvements in computational speed with multiple tank scenarios due for public release in fall of 2022.

HD Station at NREL's Campus

Thank You

www.nrel.gov

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Technical Backup and Additional Information

Technology Transfer Activities

- NREL has a license agreement with Kyushu University and continues to improve the H2FillS model – a new version of HD-H2FillS will be released at the end of the project.

- The experimental data generated within this project is expected to have a significant impact on the understanding of fast fills on vehicle systems within the medium- and heavy-duty market

Progress toward DOE Targets or Milestones

- The main target this project is pursuing is the ultimate target for Hydrogen Fill Rate as set in Table 1 of DOE's program record titled, "Hydrogen Class 8 Long Haul Truck Targets" at 10 kg/min GH2 mass flow rate.

Source: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

Special Recognitions and Awards

None

Publications and Presentations

- T. Kuroki, K. Nagasawa, M. Peters, D. Leighton, J. Kurtz, N. Sakoda, M. Monde, Y. Takata. Forthcoming. "Thermodynamic Modeling of Hydrogen Fueling Process from High Pressure Storage Tanks to Vehicle Tank."
- A. Charolais, F. Ammouri, E. Vyazmina, Q. Nouvelot, T. Guewouo, M. Greisel, M. Gebhard, T. Kuroki and S. Mathison, “Protocol for Heavy Duty hydrogen refueling: A modeling benchmark”

Flow Control Valve Characterization

Flow Control Valve Characterization Progress

- 6 tests were completed to characterize the heavy-duty dispenser flow control valve:

Test	FCV Setpoint (% Open)	Station Mass Change (kg)	Flow Time (s)	Average Flow Rate (kg/min)
1	10%	5.43	33	9.87
2	20%	6.11	33	11.11
3	30%	7.92	33	14.40
4	50%	7.95	29	16.45
5	75%	12.94	29	26.77
6	100%	14.96	27	33.24

- Observed at or above 10 kg/min average flow rates over short duration (~30 seconds) flow testing.
  - 100% open FCV test resulted in fueling nearly ~15 kgs in ~27 seconds.
  - Rapid pressure drop in bulk gas storage tanks resulting in significant temperature drop – not outside manufacturers equipment specifications but will require monitoring.
- Observations made during flow tests facilitated the creation of a bulk gas storage bank switching methodology that was implemented and tested.
- Flow control valve characterization allowed confidence in station operation to meet major project milestone.

FY22 Testing and Simulation – Objectives of Varying Parameters

Parameter	Experiments	3D CFD	H2FillS
APRR	• **Demonstrate fueling @ 10 kg/min ave** • Understand the effect of APRR on BGT and GT distribution	• **Understand the effect of APRR on BGT & GT distribution** • **Determine delta between BGT and GT_maximum.**	• **Validation** of BGT under wide variety of APRR • **Validation** of P, T from storage to tank inlet
T_{fuel}	• Understand the effect of T_{fuel} on BGT and GT distribution	• **Understand the effect of T_{fuel} on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under wide variety of T_{fuel} • **Validation** of P, T from storage to tank inlet
T_{soak}	• Understand the effect of T_{soak} on BGT and GT distribution	• **Understand the effect of T_{soak} on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under wide variety of T_{soak}
Defueling	• Part of the process after each fill	• Determine GT distribution • Accurately calculate BGT	• **Validation** of BGT under variety of defueling rates
Inlet Nozzle	• Understand the effect of nozzle direction on BGT and GT distribution	• **Understand the effect of nozzle direction on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under different nozzle directions
Tank Type	• Understand the effect of tank type on BGT & GT distribution	• **Understand the effect of tank type on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under different tank types

FY22 Testing and Simulation – Fueling Conditions for Model Validation

Parameter	3D CFD / Experiments *	H2FillS
APRR (MPa/min)	28*, 20**, 13***, 7, 2 • *10kg/min for 30 kg*, 45 kg**, 70 kg*** CHSS*	3D runs + All experiments
T_{fuel} (°C)	T40 (-36), T30 (-28), T20 (-20), T10 (-10), TA (Ambient)	3D runs + All experiments
T_{soak} (°C)	50 to -30 *(function of APRR and T_{fuel} from H2FillS)*	3D runs + All experiments
Defueling	Fast, slow	3D runs + All experiments
Inlet Nozzle	Angled Up, Straight	3D runs + All experiments
Tank Type	Type IV (*primary*), Type III (*limited*)	3D runs + All experiments
GT Max	< 85 °C (all experiments) and > 85 °C (limited # CFD)	3D runs + > 85 °C
# Sims	~ 24	~ 55

** Note: This table does not include all experimental conditions – only those that will be compared with CFD*