

Optimizing the Heisenberg Vortex Tube for Hydrogen Cooling

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Co-PIs: Konstantin Matveev (WSU), Tim Cortes, Kellen Randall, & Gilbert Hegermiller (Plug Power)
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DOE Hydrogen Program Annual Merit Review May 7th 2024
DOE Project Award #DE-EE0008429

WASHINGTON STATE UNIVERSITY

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Project Goal:

Establish, via experimentation, atomistic simulations, and Computational Fluid Dynamics, that the Heisenberg Vortex Tube (HVT) can improve the following cryogenic hydrogen systems:

1. Liquid hydrogen pump volumetric efficiency by 20% through vapor separation and subcooling.
2. **<u>Liquid hydrogen storage tank boil-off losses by 20% through thermal vapor shielding (TVS).</u>**
3. Supercritical hydrogen expansion by increasing isentropic efficiency from 31% between 40-50 K to greater than 40%.

Project Overview

Timeline:

Start: 1/23/2019

BP1 extended through 9/30/2020

BP3 extended through 5/30/2024

End: 5/30/2024

Barriers Addressed:

1. Reliability & cost of LH_2 pumping
2. High cost & low efficiency of liquefaction
3. Other fueling site/terminal operations

Budget:

$2,372.2k

Federal Share: $1,897.8k

Cost Share: $474.4k

BP1 Expenditures: $965k

BP2 Expenditures: $180k

BP3 Expenditures: $544k

Total DOE Spent: $1,861k

Partners:

Project Lead: Jacob Leachman (WSU)

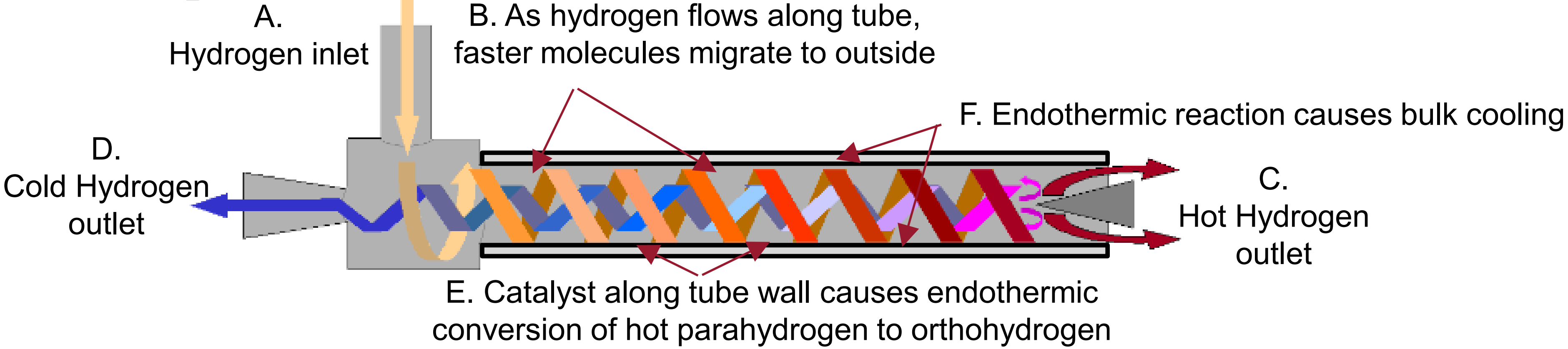
Co-PIs: Konstantin Matveev and Jeffrey McMahon (WSU), Tim Cortes, Kellen Randall, and Gilbert Hegermiller (Plug Power)

Partner Organizations: Washington State University, Plug Power

Relevance & Impact

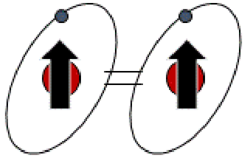
- Plug Power is the largest single user of liquid hydrogen (LH_2) dispensing ~40 tons/day. However, LH_2 utilization ranges between 93-75%. The barrier to increased utilization is boil-off/venting losses from liquid hydrogen storage facilities. Cryocooler technology cannot yet mitigate this boiloff in a cost-effective manner.

- The Heisenberg Vortex Tube (HVT) is a WSU patented technology utilizing pressurized fluid power for separation into hot and cold streams with no moving parts. The hot stream is exposed to catalyst on the periphery to drive endothermic para-orthohydrogen conversion. This has the potential to address the following DOE HFTO barriers:
  1. Improving LH_2 pumping performance by precooling the liquid prior to pumping.
  2. **Improving the cost and efficiency of liquefaction through improved ortho-para catalysis.**
  3. Improving LH_2 utilization for other fueling site/terminal operations.



Approach: Para-orthohydrogen conversion

- Para-orthohydrogen conversion is the largest phase change of any material at cryogenic temperatures and the vortex tube is the first concept to utilize for primary cooling.

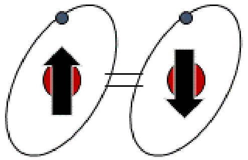


Orthohydrogen

$$\underset{(antisym)}{\psi_{tot}} = \underset{(sym)}{\psi_{vib}}\,\underset{(antisym)}{\psi_{rot}}\,\underset{(sym)}{\psi_{spin}}$$

$$\psi_{rot} = 1,3,5\ldots$$

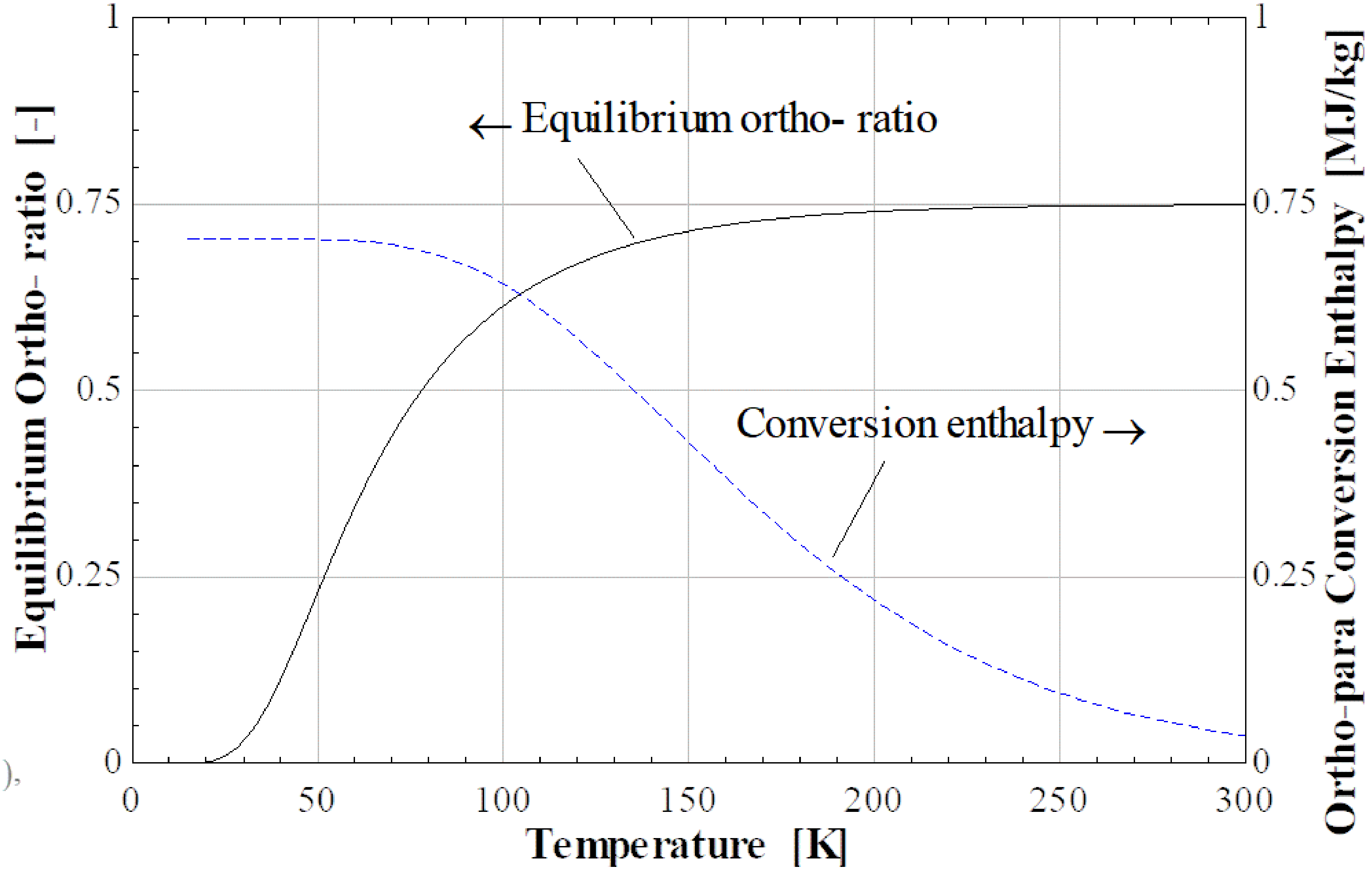
Normal Hydrogen
3-ortho:1-para



Parahydrogen

$$\underset{(antisym)}{\psi_{tot}} = \underset{(sym)}{\psi_{vib}}\,\underset{(sym)}{\psi_{rot}}\,\underset{(antisym)}{\psi_{spin}},$$

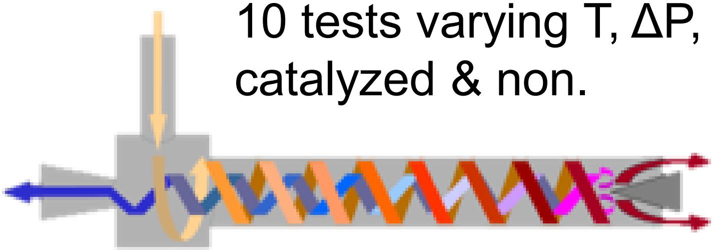
$$\psi_{rot} = 0,2,4\ldots$$



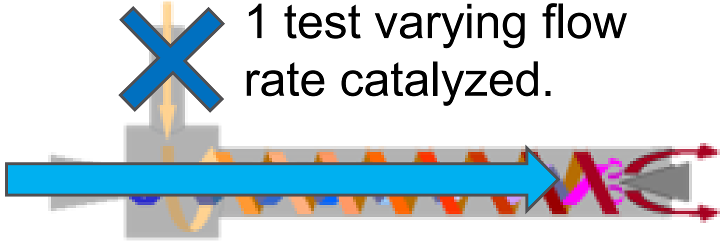
Approach: Experimental results from BP1

- Completed tests (21 total) in three different configurations to analyze catalyst sensitivity to swirl. Inlet temperature 46-52 K results shown in figure.

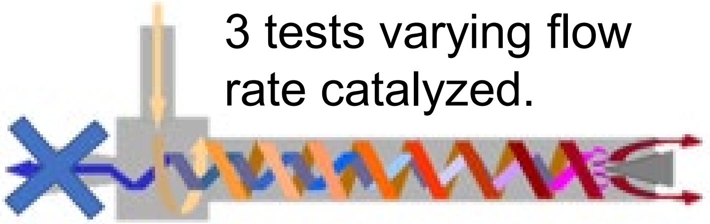
Traditional HVT:
10 tests varying T, ΔP, catalyzed & non.

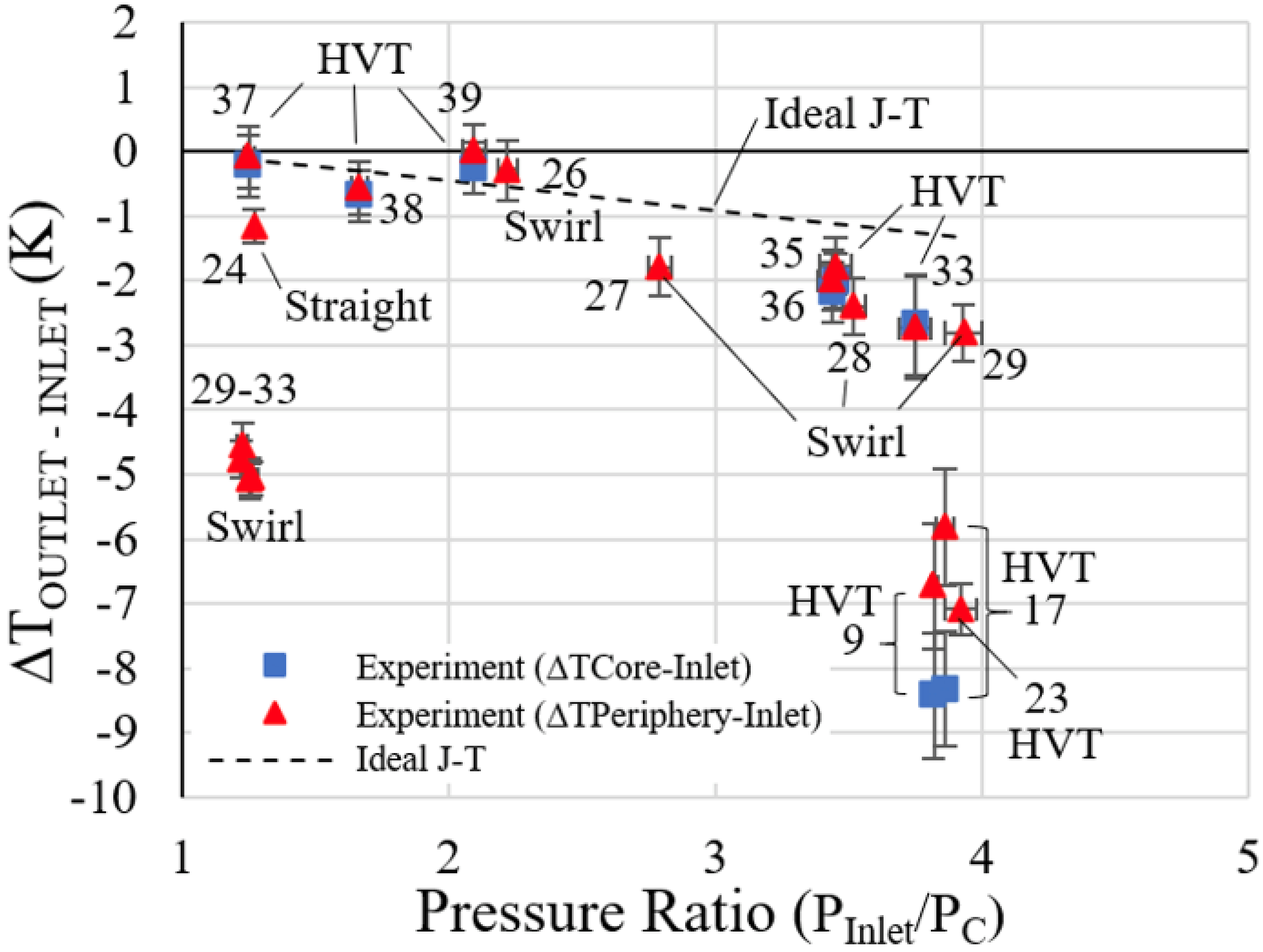


Straight flow:
1 test varying flow rate catalyzed.



Swirl flow:
3 tests varying flow rate catalyzed.

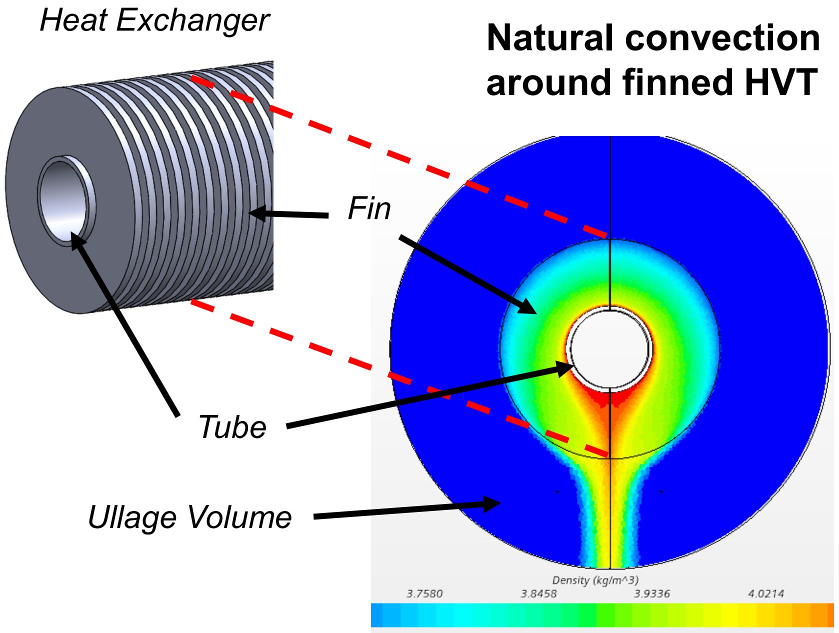


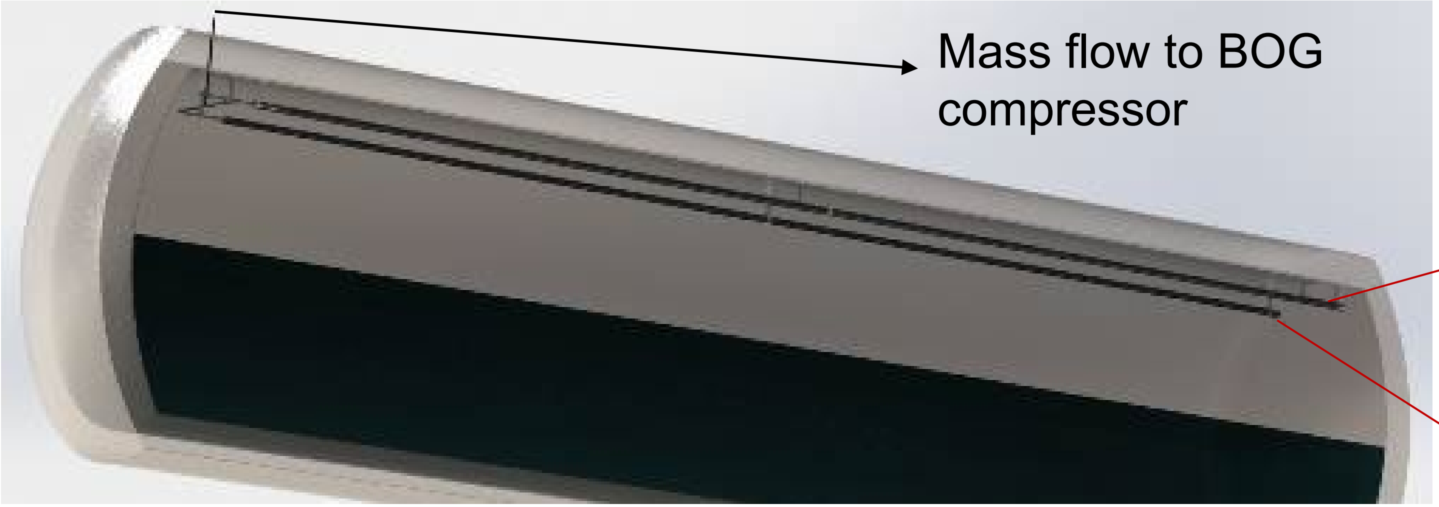


Approach: Thermal Vapor Shielding BP2

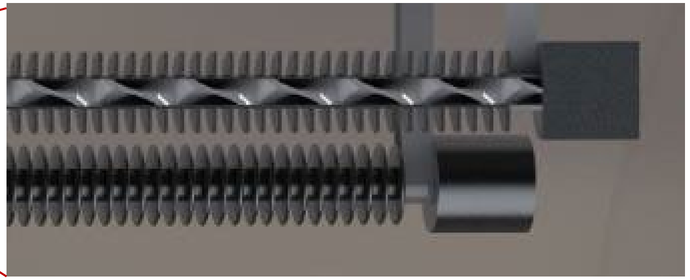
- Temperature stratification within LH2 tanks leads to increased pressure and boil-off. Plug Power utilizes Boil-off-Gas (BOG) compressors to reduce the tank pressure. However, the minimum pressure head, capacity, cost, and power requirements of BOGs are a limiting factor.

- Para-orthohydrogen conversion to equilibrium within the vapor ullage (<77 K) of a storage tank increases the energy removed from the tank by the BOG compressor up to 35%, thereby increasing utilization by reducing hydrogen vents with no additional input power required.


Natural convection around finned HVT



- We have designed a finned HVT to maximize cooling while minimizing ΔP.



Approach:

- **Objective 1**: Refurbish the Cryocatalysis Hydrogen Experiment Facility (CHEF) for supercritical hydrogen measurements.
- **Objective 2**: Produce an optimal HVT designed with an experimentally verified Computational Fluid Dynamics (CFD) model, atomistic simulations of the catalyst performance, and 3D metal printing.
- **Objective 3**: Verify predicted performance improvements by implementing the HVT in field trials as:
    1. Subcooler to minimize liquid hydrogen pump cavitation,
    2. **Thermal Vapor Shielding (TVS) system for liquid hydrogen storage tanks, and**
    3. Supercritical hydrogen expander for reliquefaction of process gas.

Budget Period 1—Detailed Calculations of Design and Performance

Go/No-Go: Performance calculations demonstrate 5% utilization improvement. (Passed)

Budget Period 2—Validating HVT Optimizations and Constructing Field Test Articles

Go/No-Go: Experimental performance demonstrating improvements. (Passed)

Budget Period 3—Validating Field Test Article Performance (Extended to May 2024)

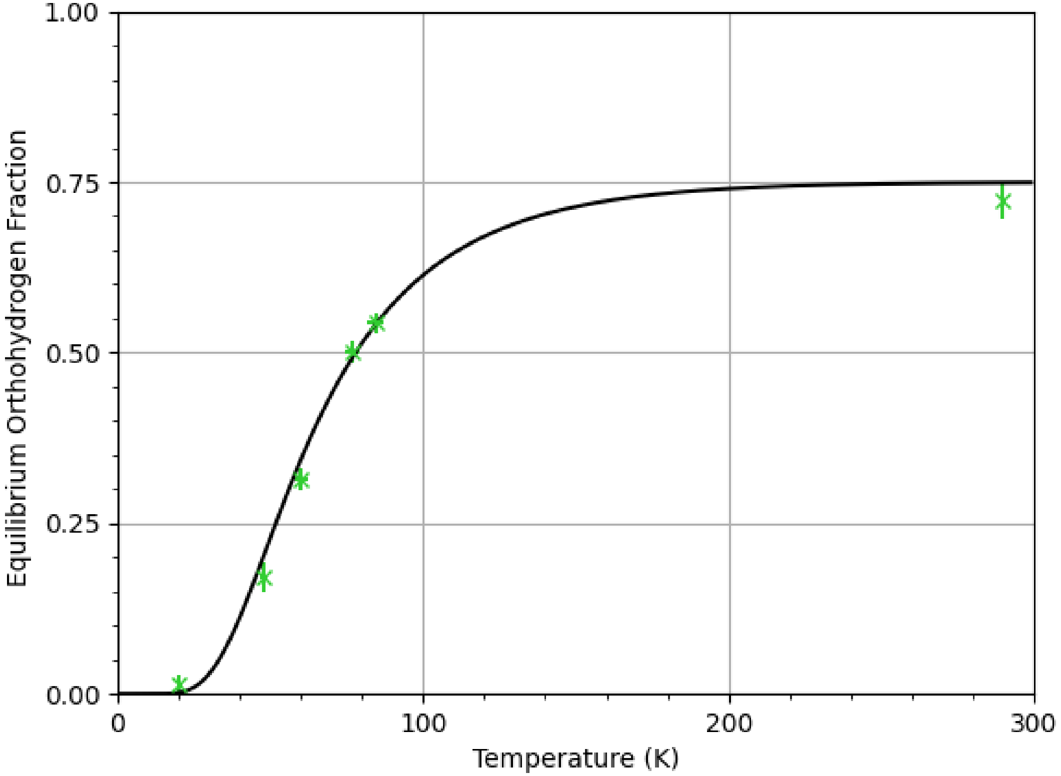
Accomplishments & Progress in BP3

Objective 1: HVT Testing in CHEF

Task 3.1.1: Utilize CHEF to conduct remaining fundamental tests of HVT operation theory and compare to field tests. *Output*: Journal publication directly addressing the fundamental behavior of vortex tubes. (12 months)

Experimental Progress BP3

Moved CHEF to a new facility. Completed sensitivity study of new absolute Raman data analysis method and confirmed ±3% accuracy of measurements in straight packed-bed flow configuration with gaseous hydrogen.



CHEF installed in new facility.

Compilation of experimental results

Configuration	Inlet Temperature (K)	Experimental (ΔTCore-Inlet)	Experimental (ΔTPeriphery-Inlet)	Cold flow fraction	Pressure Ratio	Y_{OP} (%)
Swirl	32.64	-2.58		0.415	3.25	0.939
HVT	39.81	-6.28	-5.82	0.405	3.44	1.160
HVT	36.07	-5.39	-5.4	0.374	3.35	1.153
HVT	33.78	-3.79	-3.47	0.385	3.21	1.075
HVT	44.29	-7.43	-6.34	0.38	3.55	1.167
HVT	50.56	-8.43	-6.73	0.372	3.82	1.160
HVT	50.44	0.41	0.58	0.386	4	0.958
HVT	46.11	-8.31	-5.82	0.384	3.86	1.157
HVT	52.18		-7.09	0.393	3.92	9.122
HVT	50.19	-2.68	-2.73	0.364	3.75	1.033
HVT	50.65	-2.17	-1.99	0.378	3.44	1.021
HVT	50.56	-2.01	-1.77	0.364	3.45	1.016
HVT	50.49	-0.22	-0.08	0.359	1.249	1.000
HVT	51.06	-0.69	-0.56	0.34	1.664	1.006
HVT	50.3	-0.25	0.03	0.346	2.096	0.990
HVT	31.03	-2.05	-2.86	0.406	3.21	1.124
HVT	39.81	-2.32	-1.56	0.312	3.63	1.057
HVT	49.87	-2.34	-0.55	0.351	4.13	1.027
Swirl	50.72		-2.81		3.93	2.270
Swirl	51.94		-2.39		3.52	1.954
Swirl	50.21		-4.55		1.227	6.684
Swirl	50.55		-4.77		1.221	7.021
Swirl	50.55		-5.06		1.256	7.438
Swirl	50.76		-5.07		1.253	7.456
Swirl	50.86		-5.06		1.259	7.437
Swirl	51.01		-3.41		1.204	4.988
Straight	54.23		-1.15		1.27	1.563

Conversion percentages (Y_{op}) for all tests and configurations. Steady progression from HVT to field trial configurations.

Accomplishments & Progress in BP3

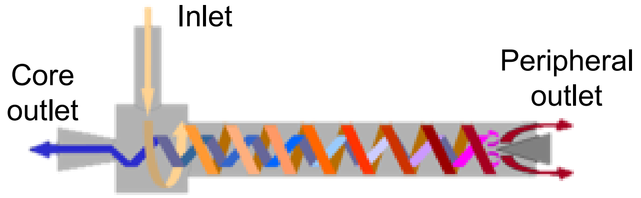
Objective 2: CFD & Atomistic Optimization of HVT

***Task 3.2.2*:** Compare CFD code to remaining fundamental HVT and field tests. Model thermal stratification in a tank. *Output:* Journal publication directly addressing the fundamental behavior of vortex tubes. (6 months)

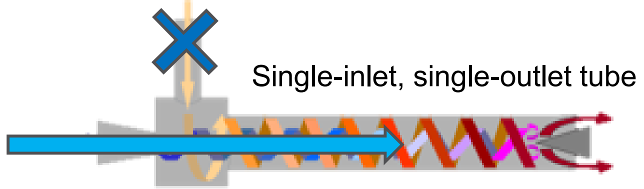
CFD Calibration Using HYPER Lab Test Data

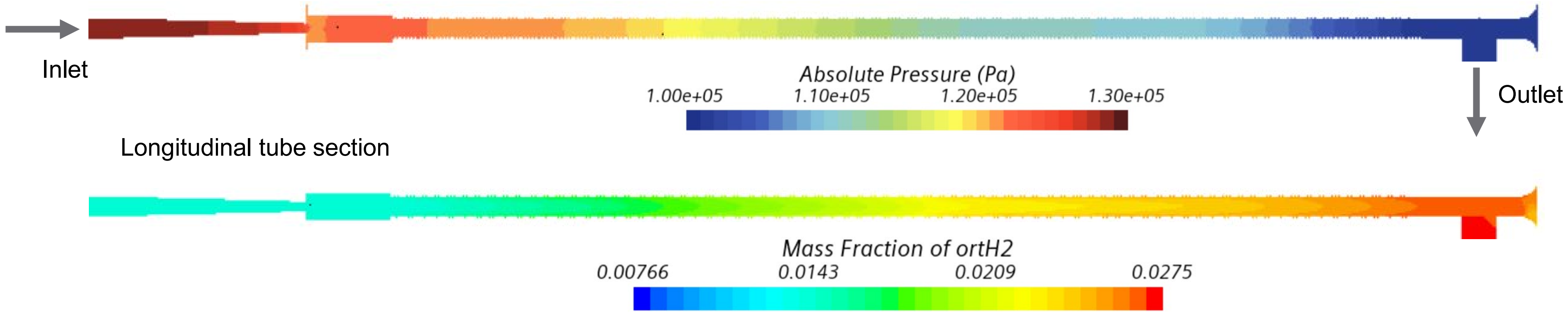
- Different tube configurations were tested in HYPER lab (catalyzed/non-catalyzed, different inlets/outlets, etc.)
- CFD model was first validated for dual-outlet, non-catalyzed setup

Inlet T	Inlet P	Core P	Core T	Peripheral T	Core T	Peripheral T
			Experiments		CFD	
53.7 K	56.6 psia	16.1 psia	52.1 K	52.7 K	52.2 K	52.7 K



- To determine the effective reaction rate coefficient in 0.25-mm-thick reaction zone near catalyzed surface, test data for the catalyzed, single-inlet, single-outlet HVT was used; an approximate match is obtained for *k* = 25 1/s
- Reaction rate: $\frac{d\rho_{ort}}{dt} = k\rho_{par}\left[y_{ort,\,equil} - y_{ort,\,actual}\right]$
- Test conditions: P_{in} = 18.70 psia, P_{out} = 14.69 psia, T_{in} = 54.32 K, T_{out} = 53.08 K, $y_{oH2,in}$ = 1.4%, $y_{oH2,out}$ = 2.9%

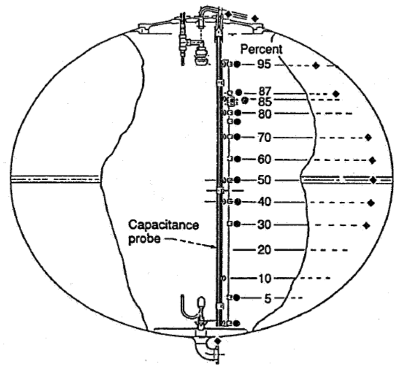




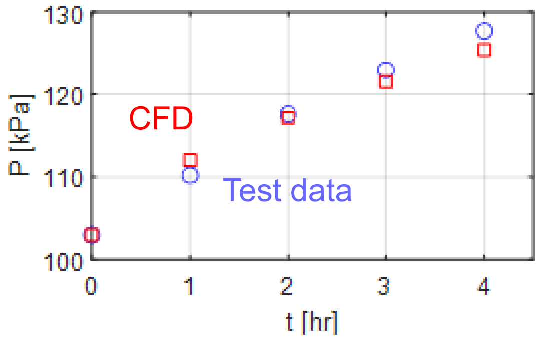
Longitudinal tube section

CFD+ROM Modeling of LH2 Tank

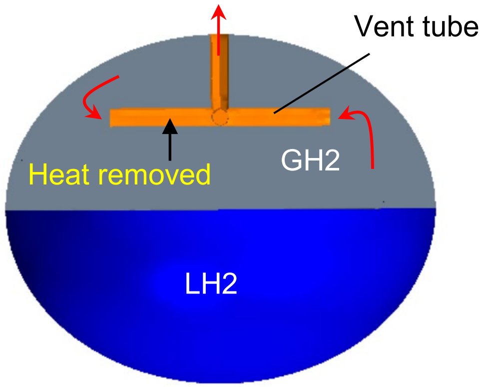
- Hybrid modeling approach: CFD simulations for ullage and reduced-order model (ROM) for liquid H2
- Validation study for self-pressurization of NASA ~2-m-diameter tank
- Also simulated an effect of cooling by para-orthohydrogen conversion of vented stream



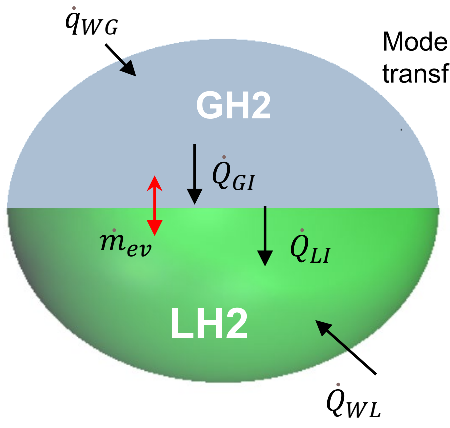
Experimental tank (Van Dresar et al. 1992)



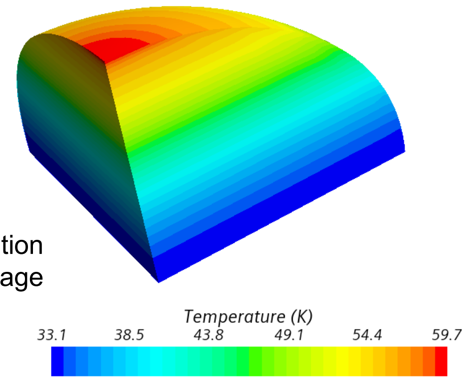
Comparison between experimental and CFD results for pressure rise



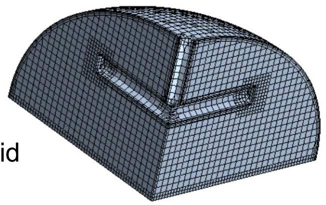
Schematic of LH2 tank with catalyzed venting tube



Modeled heat and mass transfer processes



Thermal stratification in ullage

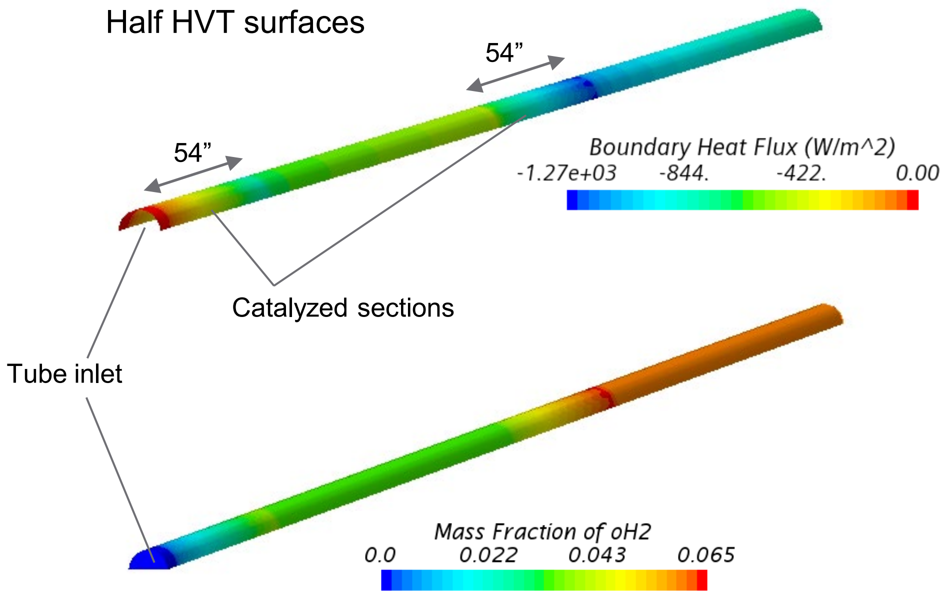


Numerical grid

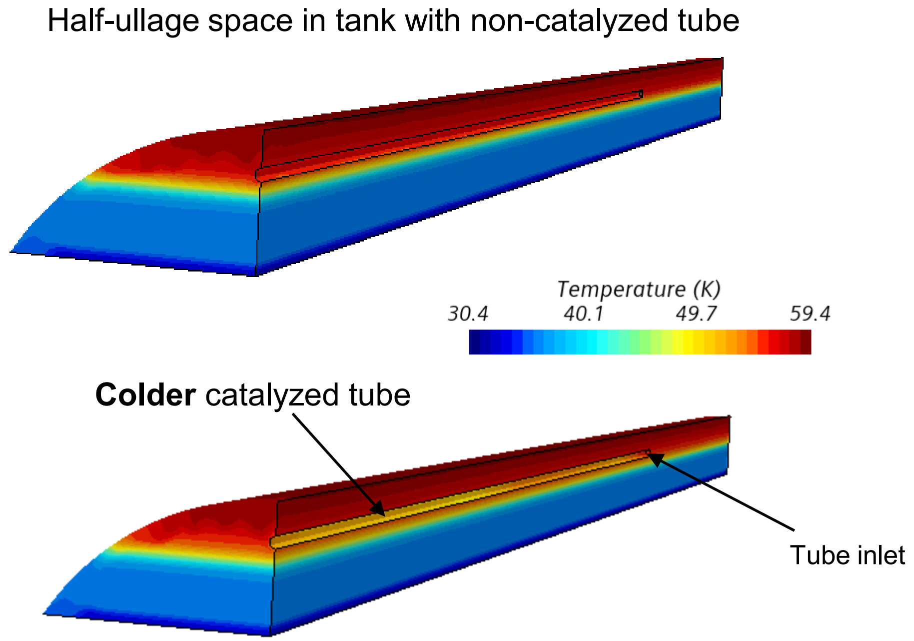
Heat leak	Venting tube	Venting rate	Boil-off loss
3.5 W/m²	Non-catalyzed	0.034 g/s	2.9 kg/day
3.5 W/m²	**Catalyzed**	**0.030 g/s**	**2.6 kg/day**

CFD Modeling of Full-Scale Tank with HVT

- Due to very different time & spatial scales, HVT and tank are modeled separately
    - HVT internal flow with para-orthohydrogen conversion using reaction rates from HYPER laboratory tests
    - tank with effective heat sink around HVT (using HVT simulation data)
- From initial test data point obtained in Plug Power LH2 tank, HVT manifested about 2.6% lower mass flow rate of vented H2 in comparison with non-catalyzed venting
- CFD modeling predicted 3.7% relative reduction of mass flow rate using HVT (with assumed 3 W/m^2 heat leak into the tank, zero-velocity & constant-pressure initial state, and after 5-min settling period)



Half HVT surfaces



Half-ullage space in tank with non-catalyzed tube

Colder catalyzed tube

Accomplishments & Progress in BP3

Objective 3: Design HVT Field Trials

Task 3.3.2: Use the field based performance tests to estimate overall costs and savings to Plug Power if adapted at other field sites. *Output:* Recommendations to Plug Power management on technical successes of project, and potential for cost savings if concept is implemented at other sites. (8 months)

Task 3.3.3: Complete Strengths, Improvements, Insights (SII) feedback for project and project team. *Output:* Recommendations for future work. (1 month)

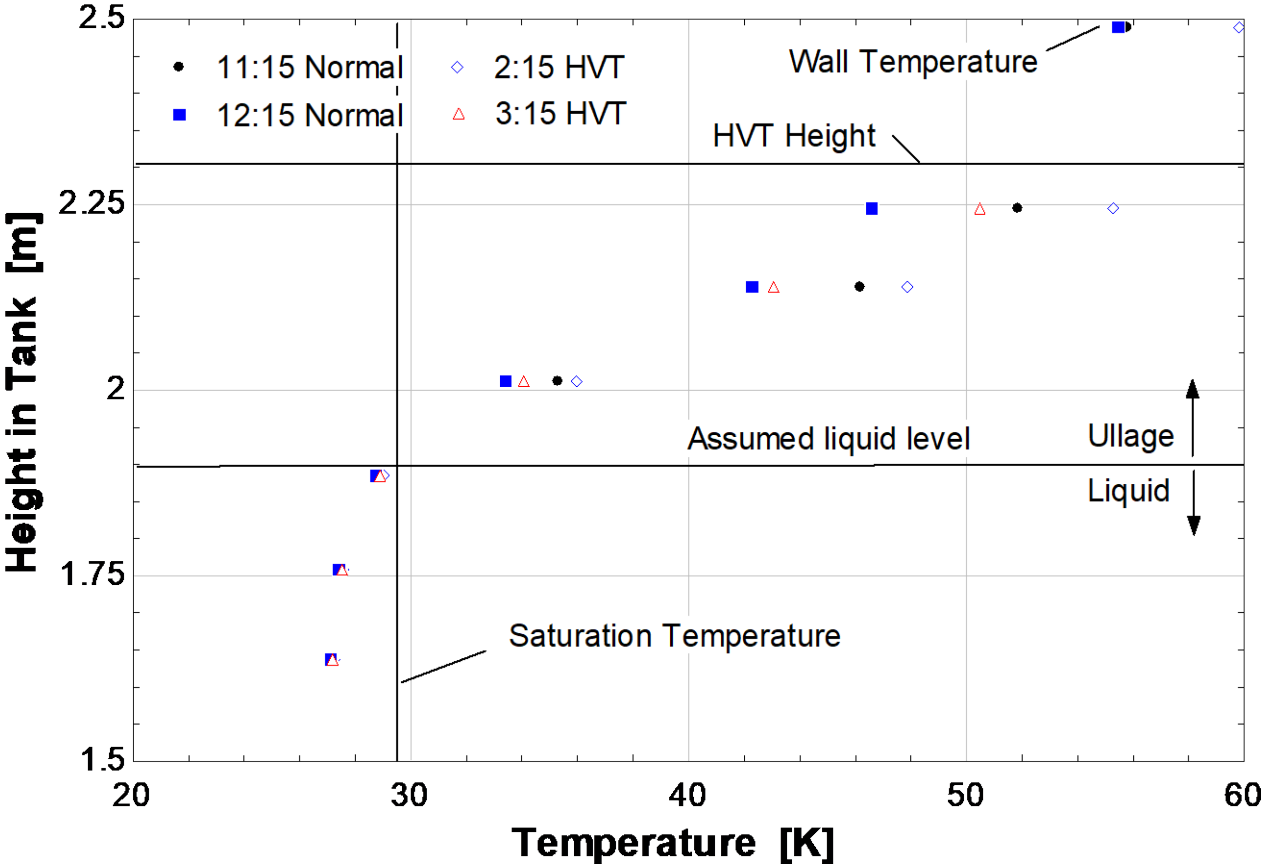
Field Trial Progress BP3

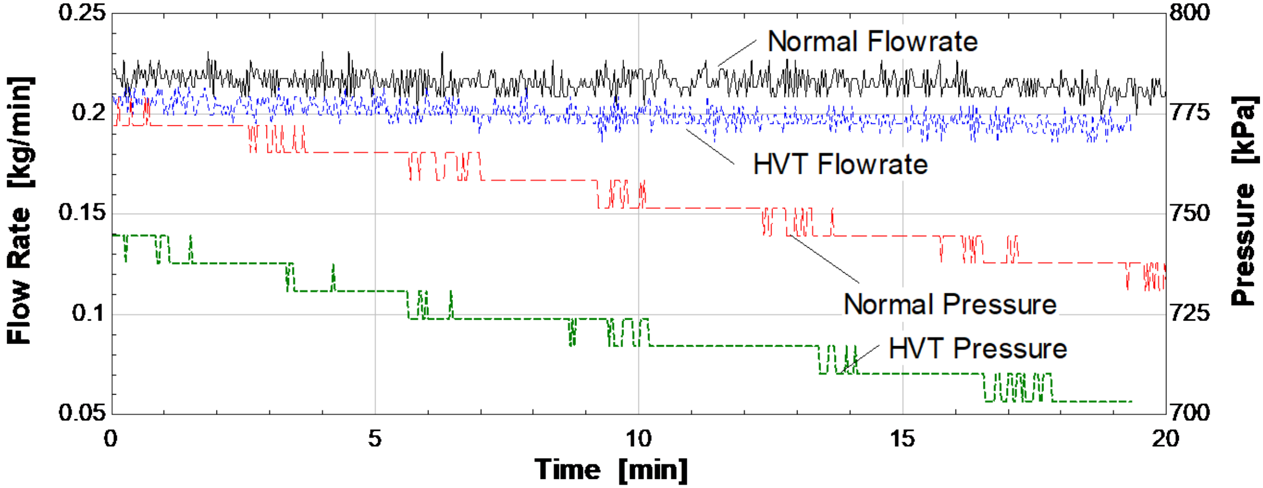
- 2022: Tank design with HVT and manufacturer selected.
- Spring 2023: Cost overshoot with catalyst supplier limits catalyst application to 30% of tube length.
- September 2023: Tank wiring harness for HVT sensors sheered off by tank manufacturer during final tank painting.
- November: Wiring harness partially repaired with 15 of 24 sensors working properly.
- January: Tank installed with 15 working sensors
- March 1st: Commissioning tank on customer site
- March 8th: AMR slides due

Image of HVT installed in tank.

Field Trial Results

- Plug Power conducted specialized commissioning tests to evaluate HVT performance. Normal pressurization and venting to BOG was compared with HVT venting to BOG via an externally operated switching valve over even 1 hour intervals.
- The HVT relative losses per day and average venting rate reduced 2.6% compared to the baseline (no HVT) case with the same overall pressure drop.
- This result agrees with the preliminary CFD modeled reduction (3.7%).
- However, this preliminary result, which was all we could obtain before AMR slides were due, is with a nearly full tank with a low ullage temperature. As the liquid level decreases the ullage space warms and models predict improved boil-off reductions with the HVT.





Team Feedback and Future Plans

- Strengths:
  1. The partner organizations were able to keep work going despite starting in 2019 and changing several staff during the project duration.
  2. The teams kept a positive attitude throughout and worked constructively to adapt to project changes, staff changes, and challenging setbacks.
- Improvements:
  1. Accounting for supply chain disruptions and delays was a substantial challenge during COVID.
  2. Three no-cost extensions due to supply chain delays was challenging to keep students and staff supported on the project.
  3. WSU's navigation to a new budgeting system during the middle of the project was far from optimal.
- Insights:
  1. Ordering long lead time items as soon as possible is essential.
  2. The good-faith efforts and patience of all partners WSU-Plug Power-HFTO were essential in keeping this project going.
- Future Collaborative Efforts: WSU and Plug Power are continuing liquid hydrogen tank modeling work via MS thesis that will incorporate future test results.

Image of finished field trial tank.

Responses to prior reviewer comments (2022)

- Q2: Accomplishments and Progress
  - "While the poster states that the conversion rates were confirmed experimentally, there is no data or results to back this up." Slide 6 (which has been included in AMR presentations since BP1) shows a compilation of measurement results. We've included slide 11 to specifically show all measurements.
- Q3: Collaboration and Coordination
  - "It is unclear whether the proprietary nature of the work or application prevents disclosure or presentation of the data." See the response to Q2 above. The only information that Plug Power has been careful to secure with this project is the financial savings of adding this technology to a site. As stated in BP1 Go/No-Go, "It is reasonable to assume that 50% of our sites will be positively impacted by the HVT-TVS."
- Q5: Proposed Future Work
  - "The project is planned to finish in June 2023 but has failed to provide lab result comparisons. It is unclear from the poster whether the project is implemented into a full-scale dedicated LH2 tank for field testing." Field trials were delayed by tank manufacturing setbacks and pushed to 2024. Lab scale results have been compared with field trial data and shown in this presentation.
- Weaknesses and Recommendations
  - "The project's modeling work needs lab validation that either has not yet been completed or was not presented. Industry should evaluate the usefulness of the project's technology." The modeling work has been validated at both the laboratory and field levels in this presentation. It was not included in the prior poster for compactness. Plug Power is still evaluating performance gains of the HVT over extended field trials to evaluate cost/benefit of the HVT.

Collaboration and Coordination

- Washington State University (WSU) is the prime grant awardee and responsible for Objectives 1 & 2.
- Plug Power is a sub-awardee and responsible for Objective 3.
- WSU and Plug Power meet virtually every other week to discuss project progress and monthly with a DOE program representative.

Image of finished field trial tank being filled.

Remaining Challenges and Barriers

- Low-cost, high-activity para-orthohydrogen catalysts were identified as a barrier to future implementation of the HVT in more LH2 tanks. Catalyst prices came back substantially higher than early estimates.
- Detailed measurements of ullage space behavior in relevant tanks was identified as a persistent issue faced by the industry. These results limited the applicability of tank models and forced us to develop our own. Verification of these models requires more robust tank instrumentation and measurements.

Proposed Future Work

- N/A

Summary & Thank you!

Since January of 2019 our team has:

- Retrofitted the Cryocatalysis Hydrogen Experiment Facility (CHEF) for 70 bar measurements, a cycle time less than 2 days, and the first continuous flow cryogenic Raman spectroscopy system for para-orthohydrogen analysis; subsequently allowing over 100 tests in various flow configurations.
- Developed a computational analysis system that utilizes full atomistic simulations of para-orthohydrogen catalysis to create lookup tables for computation fluid dynamics (CFD) simulations. These results have been validated by experiment and used to optimize the HVT for a Plug Power application.
- Designed a novel HVT-based heat exchanger to reduce the ullage temperature within Plug Power liquid hydrogen tanks. This design was tested during field trials in 2024 at a Plug Power site where the HVT could be tested side-by-side with conventional extraction methods. The HVT showed improved ullage temperature/pressure and associated reductions in venting similar to CFD predictions. Further testing will verify this performance over a wider array of tank conditions.