Design and experimental measurements of a Heisenberg Vortex Tube for hydrogen cooling

E Shoemake[1], C Bunge[2], J Leachman[3]

HYdrogen Properties for Energy Research (HYPER) Laboratory, Washington State University, Pullman, WA 99164-2920 USA

[1]elijah.shoemake@wsu.edu, [2]carl.bunge@wsu.edu, [3]jacob.leachman@wsu.edu

CEC/ICMC 2017 JULY 9-13 MONONA TERRACE MADISON, WI

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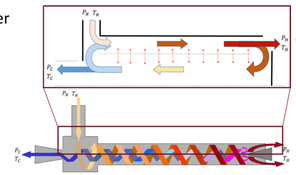
Motivation

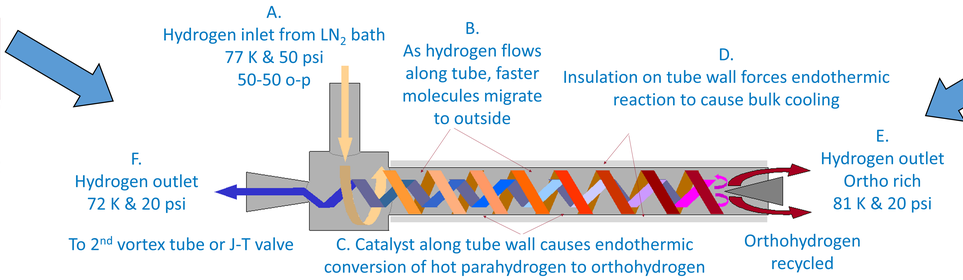
Ten hydrogen liquefaction facilities produce hydrogen in North America[1]. The increased mass per delivery of liquid hydrogen is likely to become increasingly important as automotive hydrogen refueling stations see increased utilization. The cost to produce and deliver liquid hydrogen varies based on location and the delivery costs can be 3-4 times the production costs. To address these needs, the Department of Energy has specified the following targets for hydrogen liquefaction:[2] 1.improving liquefaction cycle efficiencies from a figure of merit (FOM) of 0.35 to >0.5, 2. lowering liquefier capital costs below $2.5 million/tonne per day, and achieving these metrics in systems as small as 5 MTPD.

Ranque-Hilsch Vortex Tube

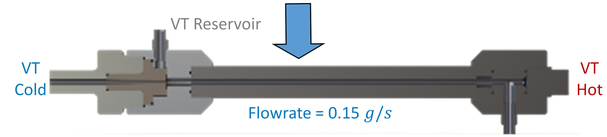
In the vortex tube, injected compressed gas forms a vortex. The outer fluid of this vortex flows toward one exit and core back past the injector through the other exit.

1. Radial change in pressure promotes temperature drop in core.
2. Heat pumping from the cold core to the hot occurs due to viscous work streaming between the streams.
3. More complications arise from frictional heating, turbulence, recirculation, etc.



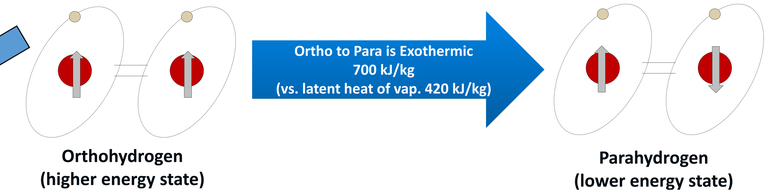


* All values subject to measured performance dependant on system cycle, catalyst selection, and vortex tube geometry



Our custom vortex tube design for cryogenic hydrogen.

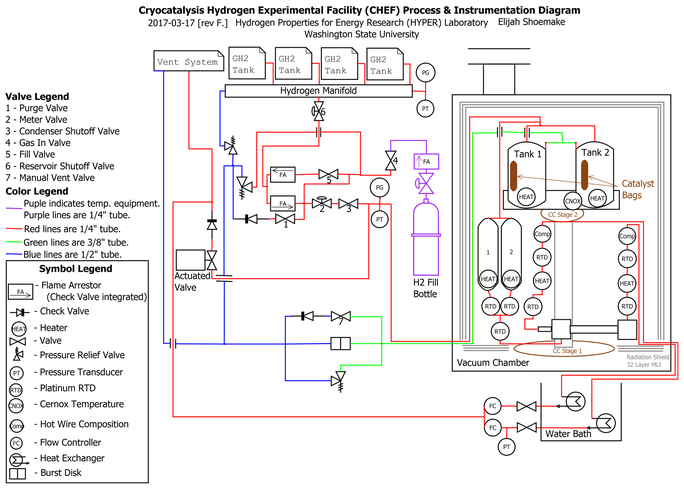
Spin Isomers of Hydrogen and their Catalysis



Hydrogen exists in two quantum states: orthohydrogen, where quantum spin state of each hydrogen atom in the molecule is aligned; and parahydrogen, where the hydrogen atoms have differing quantum spin states.

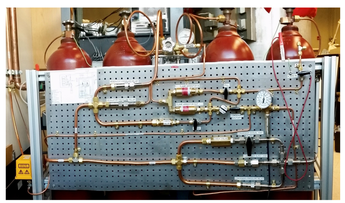
Conversion between these forms takes weeks to months as a gas, but will boil half of liquid hydrogen stores in a week. By using catalyst in the liquefaction cycle to promote conversion as a gas, this heat can be released earlier in the cooling process, where cooling is more efficient.

Experimental Design



Process:

1. Hydrogen is filled into the gaseous reservoir tanks to 70 psia. It is then allowed to slowly fill the condenser tanks, cooled to ~20K. As the hydrogen cools and condenses, new hydrogen is cryopumped into the condenser tanks. At the bottom of the condenser tanks is a catalyst that ensures conversion to parahydrogen.
2. When pressure drops to 50 psia, the reservoir tanks are topped off with more hydrogen. This liquefaction process continues until 4 L are liquefied in the tanks.
3. The reservoir tanks are shut off from the condenser tank. A heater on the bottom of the tanks boils off hydrogen to increase tank pressure. This hydrogen flows through reactors 1 and 2, where it is warmed to the desired inlet conditions, then through the vortex tube, and finally out through mass flow meters to the building vent.
4. An inlet temperature for the vortex tube is recorded, as well as temperature at each outlet. The hydrogen is then warmed to 130 K and flows past a hotwire thermal conductivity probe to measure composition.



Heisenberg Vortex Tube (HVT)

The HVT principle works to combine these two previous discoveries to create a device that utilizes para-orthohydrogen catalysis as an energy shuttle to transfer energy from cooler parts of a liquefaction cycle to warmer parts of the liquefaction cycle where cooling is more efficient.

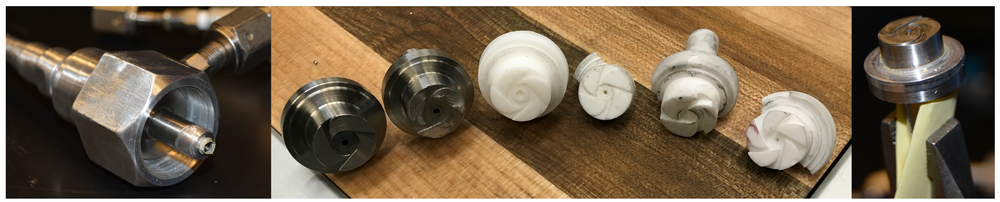
1. In the case above, hydrogen enters the vortex tube at 77 Kelvin, 50% parahydrogen due to the ease of precooling and catalyzing a hydrogen stream with a liquefied nitrogen heat exchanger.
2. After entering the vortex tube, the hydrogen splits into two streams. On the outside of the tube's flow, work is being done on the hydrogen and it heats, in the inside of the flow the hydrogen cools.
3. If a catalyst is placed on the tube wall, the warmed hydrogen stream will convert to a higher orthohydrogen concentration —an endothermic process, and the reverse of the typical exothermic ortho to parahydrogen conversion.

We had three test cases to examine performance of the HVT:

Smooth, uncatalyzed tube— This tube had a completely smooth interior, 9/64 inches in diameter by 7 inches long. No catalyst was applied to the inside of this tube.

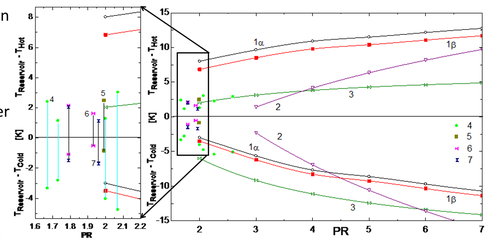
Threaded, uncatalyzed tube— The interior of this tube was threaded with an M4 – 0.7 thread and is 7 inches long. No catalyst was applied to the inside of this tube.

Threaded, catalyzed tube— The interior of this tube was threaded with an M4 – 0.7 thread and is 7 inches long. Ruthenium catalyst was coated on the inside of the tube, covering the threads. Due to the requirements of the catalysation process, this tube was cut in half to be coated and then rejoined in the vortex tube.



Results

As can been seen above, results align well with current theoretical predictions, although most current models do not extrapolate well to these low pressure ratios. For further information on theoretical models displayed, please see our other presentation on cryogenic vortex tube models, "Analytical and numerical performance models of a Heisenberg Vortex Tube."



Legend

1α — Extended heat exchanger model
1β — Extended heat exchanger with maximum o-p conversion
2 — Liew model
3 — Ahlborn Gordon model
4 — CFD Predictions
5 — Smooth, uncatalyzed experimental data
6 — Threaded, uncatalyzed experimental data
7 — Threaded, catalyzed experimental data

At a pressure ratio of ~1.96:

1. Threading the tube shows decreased cooling by 38%±50% (within experimental error).
2. The catalyzed tube increases cooling by 233%±268% over the threaded control and 105%±100% over the smooth control. This shows increased cooling outside of experimental error when comparing to the smooth control, but within experimental error for the threaded control.

At a pressure ratio of 1.80:

1. The catalyzed tube increases cooling by 38%±56%, again showing possible cooling due to catalysation, but within experimental error.

Tube	Smooth Tube	Threaded Tube	Threaded Tube	Threaded Tube	Threaded Tube
Catalyst	None	None	None	Ruthenium	Ruthenium
Pressure Ratio	1.99±0.09	1.80±0.09	1.93±0.09	1.79±0.09	1.96±0.09
Cold Fraction	0.37±0.006	0.38±0.006	0.44±0.006	0.38±0.006	0.42±0.006
Cold Temp Drop	0.83±0.35 K	1.08±0.35 K	0.51±0.35 K	1.49±0.35 K	1.70±0.35 K
Hot Temp Rise	2.50±0.35 K	2.16±0.35 K	1.63±0.35 K	2.06±0.35 K	1.13±0.35 K

Conclusions:

1. The Heisenberg Vortex Tube appears to be improving upon a traditional vortex tube, although only one measurement so far has been able to show enough improvement to be outside experimental error.
2. Further testing needs to be done, higher pressure ratio testing will help get results outside error.

[1]Weeda M, Elgowainy A. Large-Scale Hydrogen Delivery Infrastructure. Task 28 Final Report. Westerduinweg 3, 1755 LE Petten, The Netherlands: International Energy Agency Hydrogen Implementing Agreement; 2015. ISBN: 978-0-9815041-8-6.

[2]Office of Energy Efficiency and Renewable Energy. Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan. https://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22: Department of Energy, August 2015.

Acknowledgments

This material is based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), specifically the Fuel Cell Technologies Office. This work was also supported by a NASA Space Technology Research Fellowship.