Company goal

Protium Innovations LLC designs, manufactures, and installs hydrogen handling technologies.

Problem

Intermittency of renewable energy sources such as wind and solar cause considerable curtailment issues for power regulating authorities. As more renewables are added to the grid, new low-cost, highly variable energy storage methods are required. At the same time, fuel cell electric vehicles (FCEVs) and material handling equipment are coming into market with limited fueling options. As hydrogen infrastructure continues to develop, liquid hydrogen (LH2) production and delivery are estimated to become the dominant dispersal method. Yang and Ogden (2007) [1] evaluated the lowest cost hydrogen delivery mode (high pressure gas delivery, liquid delivery, low pressure pipeline) including transmission (from production site to city) and distribution within city limits. Liquid hydrogen delivery was the preferred transmission method in 43% of the cases. For distribution within city limits, liquid hydrogen was the preferred method for 50% of the cases, with high pressure gas delivery and pipelines comprising the remainder of scenarios. However, only 8 LH2 liquefaction facilities exist in North America, only one of which is free of carbon emissions, while lack of geographic distribution drives high delivery costs. There is clearly insufficient LH2 production capacity to address the future demand, and a new method for low cost distributed hydrogen generation and liquefaction is required to alleviate strain on power grids via fuel cells power generation, while fueling the rapidly evolving fuel cell vehicle fleet.

Although a host of energy storage technologies are being considered to ease strain on the power grid, none of these technologies directly aid the nascent FCEV fueling market. The FCEV market is currently sustained by government subsidies to create the minimum number of refueling stations to support a hydrogen economy that are maintained by regular high pressure gaseous hydrogen (GH2) or LH2 deliveries. Each LH2 tanker can deliver 13x the mass of GH2 tube trailers. As a result, LH2 is primarily used by the material handling equipment sector, which is self-sustaining, however limited by local LH2 availability. In remote locations or for customers demanding carbon emission free hydrogen, spending the capital to construct an on-site water electrolysis system for hydrogen production is often necessary. Because the current FCEV market is small, the established large scale hydrogen liquefaction plants are sufficient, but to sustain the anticipated hydrogen demand, cost of liquefaction must decrease with carbon emission and liquefaction capacity must increase while becoming more equally distributed across the country.

Solution

Our technology opens a market for distributed small-modular hydrogen liquefaction that can be integrated with standard hydrogen production methods to enable expansion of the hydrogen fueling infrastructure in an economical and scalable solution.

---

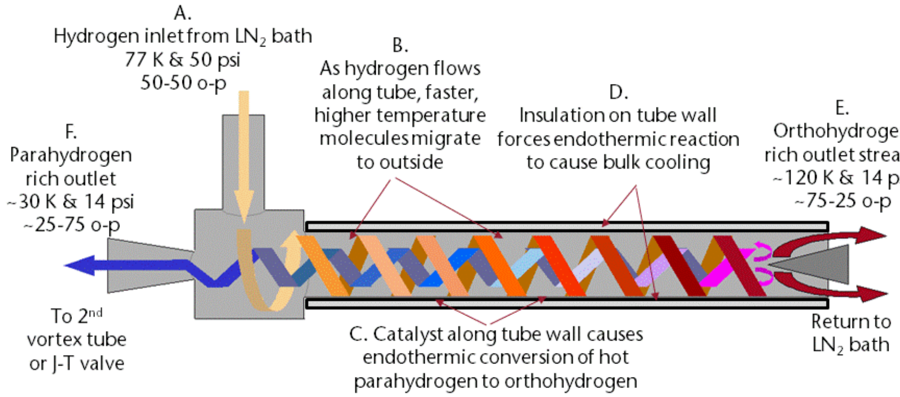
[1] C. Yang and J. Ogden. 2007. Determining the lowest cost hydrogen delivery mode. Institute of Transportation Studies. University of California. Davis, CA.

State Of The Art

Current small-modular hydrogen liquefaction, as used in laboratory environments, utilizes heat exchange with helium refrigerant at an energy consumption rate ~20 times higher than large scale conventional refrigeration cycles operating with the dual-Claude cycle. Large-scale conventional cycles currently operate with either turbo-expansion, piston expansion, or Joule-Thomson expansion to accomplish the sub-77 K refrigeration necessary for liquefaction at 21 K. All of these approaches must remove the latent heat of orthohydrogen-parahydrogen conversion via mass flow through an activated catalyst bed and require significant commodities of scale to be efficient. Catalyst beds are operated below 77 K and generate an exothermic heat load that requires either liquid nitrogen boil-off, or directly adds to the sub-77 K refrigeration load. The exothermic latent heat load from orthohydrogen-parahydrogen conversion is nearly equal to the sensible heat load to cool the hydrogen from 77 K to 21 K. Consequently, the two extant liquefaction technologies are not energy efficient nor suitable for widely distributed, small to medium scale liquefaction systems.

Innovation

We have filed a provisional patent and seek to develop a proof-of-concept that kinetic parahydrogen-orthohydrogen conversion and separation can be used for higher efficiency primary cooling in any hydrogen liquefaction cycle design. The concept of kinetic parahydrogen-orthohydrogen conversion and separation in a vortex is shown in the figure below.



Hydrogen enters the vortex tube at A from a liquid nitrogen bath at 77 K, ~50 psi, and 50-50 ortho-para composition. As the hydrogen enters the vortex at B, faster, higher temperature molecules migrate to the outside of the tube and slower, colder molecules migrate towards the inside. The outer, higher temperature fluid is likely near ~120 K. At this elevated temperature the equilibrium ortho-para composition shifts to nearly 70 % ortho, and a catalyst along the outer tube wall catalyzes the endothermic conversion (C in the diagram). Insulation along the outer tube wall (D in the diagram) necessitates that the thermal energy required for the endothermic conversion is provided by the surrounding fluid, driving bulk cooling. The now orthohydrogen rich outer stream is separated from the vortex tube (E in the diagram) and recycled. The remaining parahydrogen rich fluid in the core region of the vortex is extracted at point F in the diagram, where it can be fed to a second vortex tube or through a conventional J-T valve or flash separator for final liquefaction. Efficiency improvements approaching 20 % over the current state of the art are possible with this scalable and modular approach. Our specific innovation lies in the use of the vortex tube with hydrogen gas and a catalyst to liquefy the hydrogen, not in the design of the vortex tube itself. Vortex tubes are widely used in industrial settings for spot heating and cooling using compressed air. Our demonstration will consist of a poster presentation illustrating results from laboratory tests of our prototype hydrogen liquefaction system.

Market

Our business model provides two synergistic services: 1) grid-level renewable power storage and regulation capabilities for energy and regulatory organizations, and 2) distributed liquid hydrogen production and delivery for vehicle and industrial gas markets.

Power grid regulating

Utility companies continually balance energy demand vs. production via curtailment-varying power generation to non-optimal levels to regulate overall grid power. Despite integration of renewables, the intermittent nature of solar and wind has caused some locations to already approach curtailment limits. When curtailment limits are exceeded, spot market power pricing can go negative, meaning energy companies will pay for power removal from the grid. Highly variable stationary electrolyzers can produce hydrogen during negative and low price intervals, or consume stored hydrogen for power generation during peak demand. Our proposed liquefaction technology allows hydrogen production to be stored for future energy use, while opening new revenue streams in cases of over production of LH2 from renewables.

Material Handling and FCEV markets

Fuel cell powered material handling equipment is quickly outpacing LNG fueled and battery powered equipment due to reduced annual cost of ownership, quicker refueling, reduced GHG emissions, and extended product life. Material handling warehouses using 100’s – 1000’s of forklifts have on site storage for liquid hydrogen delivery and are limited to geographical locations close to hydrogen liquefiers. Our liquefier technology, coupled with an electrolyzer, would allow on site liquid hydrogen production, liquefaction, and storage at lower cost than delivery. Production may be carbon free depending on electric source.

On the FCEV front, Honda, Hyundai, and Toyota are currently releasing FCEVs that will require a nationwide infrastructure to support public adoption of the new technology. Hydrogen fueling stations will require a continual supply of hydrogen fuel, whether manufactured on site or delivered from distributed production sites. Hybrid electric vehicle sales increased 106% YOY between 1999 and 2012, while the recent rollout of plug in electric vehicles (PEVs) have sold at a rate of 62% YOY between 2011 and 2014 with 119,710 units sold in 2014. If we assume an adoption rate for FCEVs similar to PEVs, which offers increased mileage over PEVs and refueling times comparable to internal combustion engine vehicles, with initial year sales of 15,000 units (less than 1st year sales for PEVs), current total hydrogen liquefaction capacity will be exceeded in 3.5 years, assuming 50% delivered as liquid.

Customers

Our customers from the power utilities sector include Puget Sound Energy and Avista Utilities. Dr. Jake Leachman has proposed the use of a stationary fuel cell for load balancing grid power to the Bonneville Power Administration, with excess power being used to produce liquid hydrogen for compact storage and potential resale. We intend to engage Avista utilities with a similar proposal as well and to use the electrolysis unit to efficiently incorporate electricity into the grid from their recently completed Palouse Wind project. Dr. Jake Leahman has also initiated dialogue with Plug Power, a leading fuel cell powered material handling solution provider, to discuss the potential for on-site hydrogen liquefaction. Microsoft has expressed interest in using fuel cell backup power for their server site in Quincey WA while using the hydrolyzer/liquefier to produce liquid hydrogen on site. Excess LH2 may then be sold on the hydrogen market. A similar proposal will be made to REC Silicon in Moses Lake WA, a producer of solar grade polysilicon. Production of polysilicon requires hydrogen gas for oxide control and the ability to produce high purity, carbon-free LH2 onsite for production purposes precludes the need for delivery. An additional customer class is represented by those who require LH2 delivery for FCEV refueling stations. We are currently negotiating a partnership with Stratos Fuel to develop and install an FCEV fueling station on the WSU campus. The FCEV modular fueling station project was developed at WSU that Protium Innovations LLC will likely receive IP licensing rights to.

Competition

Small scale hydrogen liquefaction is the technologic advantage to our hydrogen production system. Well established industrial gas suppliers such as Praxair, Air Liquide, Linde, and Air Products provide on-site hydrogen production units but are typically based on steam methane reformation (SMR). Only Praxair and Linde offer H2 production via hydrolysis. ITM Power in the UK manufactures modular H2 electrolysis systems that store and dispense gas at 350 bar. Hydrogen Energy and Technology Corporation (British Columbia) manufactures by-product hydrogen production facilities that are capable of liquefaction most likely using the industry standard Claude cycle. High pressure is typically used to increase gas density and reduce storage size, however, high pressure gas storage costs 10 – 20x what liquid hydrogen storage costs on a per kilogram basis (Yang and Ogden, 2007). In summary, there are currently no modular, small-scale hydrogen liquefaction systems available on the market.

Commercialization plan

Manufacturing

All components of our hydrolysis/liquefaction system are commercial off the shelf parts (COTS) to minimize cost, except for the vortex tube that will be custom manufactured, eventually by Protium Innovations LLC. Assembly of the system will take place at the WSU Research and Technology Park in space rented by Protium Innovations LLC by company members.

Marketing & Sales

We will make direct contact with potential customers we think may be interested in incorporating a modular on-site LH2 production service for load balancing (Puget Sound Energy, Avista), for direct use of LH2 as a fuel (Plug Power), for power back-up while selling excess LH2 production (Microsoft), or for industrial use while selling excess LH2 production (REC Silicon).

For the LH2 sales and delivery side of the company we will contact and work with hydrogen fueling stations that adopt liquid based fuel storage to establish fueling schedules and fuel costs based on electricity consumed and required profit margin to recoup capital costs for company owned LH2 production units. We will propose a joint advertising campaign with Toyota, Honda, and Hyundai to demonstrate to the public hydrogen fueling infrastructure is being established thus justifying consumer's adoption of FCEVs.

Distribution & Support

We will handle distribution of LH2 fuel via partnerships with existing LH2 delivery companies and eventually with our own fleet of cryo-tanker trucks to hydrogen fueling stations. Protium Innovations LLC will handle delivery, installation, and servicing of modular liquefaction units directly to ensure customer satisfaction. Liquefaction units that develop significant issues will be exchanged for an operational one while the defective unit is returned to Protium Innovations LLC to evaluate failure and repair as required.

Cost / Profit

We are currently assessing two profit models that include direct sales of the liquefaction units to customers, or leasing the units while retaining ownership of the equipment and excess LH2 produced. The following profit model assumes direct equipment sales for the production of LH2 for FCEV fueling stations. The proof of concept liquefaction unit will be built in space rented through the Washington State University Tech Park. Rates are $0.99 / sq. ft. and include utilities. A 30' x 30' space rents for $10,800 annually. The following table outlines costs and profits.

Overhead	30' x 30' = 900 sq ft	
	Rent ($/sq. ft./month)	$0.99
Annual rent	$10,800	
IP license (5% of sales)	$90,000	
Salaries (4 @ 50,000)	$200,000	
Total overhead	$300,800	
Cost of goods sold		
H2 electrolyzer - HGernerators (HG-50)	$400,000	
H2 gas compressor - Hydropac (C06-05-70/140LX) - 30 kW	$54,000	
compressor		$25,000

control system		$29,000
H2 gas storage (tube trailer - 300 kg @ 2350 psi)	$150,000	
LH2 storage (cryogenic tanker - 4000 kg @ 250 psi)	$650,000	
Vortex Tubes	$10,000	
Control system for plant	$25,000	
Expansion valves (2)	$5,000	
20' shipping container	$5,000	
Manufacturing hydrolysis unit + liquefier	$1,299,000	
Profits		
Liquefaction module sales price	$1,800,000	
Gross-profit Margin (LH2 module)	27.83%	
Markup (LH2 module)	38.57%	
Operating expenses (LH2 module)	16.71%	
Net Profit (LH2 module)	11.12%	$200,200

For the anticipated FCEV market, assuming a growth rate similar to that of PEVs, annual production requirement for liquefaction units would be 148 units at year 5 and 1751 at year 10 assuming only 50% of hydrogen demand to come from liquid, representing a $351M profit by year 10. The current rate of transfer from LP gas / battery electric material handling units to fuel cell powered is still being investigated, but many of the largest companies that operate distribution warehouses (Walmart, Kroger, etc.) have changed to fuel cell powered lifts and pallet jacks. We are currently evaluating this market to estimate profit potential, as well as assessing the market for grid power storage and load balancing.

Work plan and outcomes

1. Build & test prototype (April 2015) – prototype will be built using off-the-shelf parts and tested using hydrogen gas in the WSU HYPER lab. Temperature and mass flow rates of outlet gas / liquid will be measured.
2. Assess initial test results (May 2015) – use information to modify apparatus as necessary to achieve desired outcome (liquid hydrogen flow).
3. Develop CFD flow model (July 2015) – use model to identify geometric parameters critical to optimized design of vortex tube for use with hydrogen gas.
4. Built & test improved prototype (December 2015) – second generation prototype optimized for hydrogen will be built in house and tested under assumed operational conditions.
5. Identify manufacturing partner (February 2016) – request bids from local machine shops to determine unit production cost for custom designed vortex tube.
6. Determine customer requirements (April 2016) – discuss specific requirements of system with customer and incorporate into final design.
7. Start design of supporting system (July 2016) – vortex tube liquefier will require LN2 heat exchangers, low pressure hydrogen gas storage tanks, cryogenic storage tanks, and H2 gas pumps for recompressing the hot stream from the vortex tube back into the low pressure hydrogen gas storage tank.

8. Produce and install systems to satisfy initial customer requirements (December 2016).
9. Monitor supply / demand of liquefaction system to determine if it meets objectives.
10. Modify system as required to ensure specifications are met (July 2017).
11. Advance marketing tactics (August 2017) – contact potential customers in need of on-site liquefaction systems and advertise through partnership with Toyota, Honda, Hyundai.
12. Partner with alternative energy companies to provide packaged solutions for utilities load leveling requirements (August 2017).

Team

Dr. Jacob Leachman – WSU Mechanical Engineering Faculty advisor and member of Protium Innovations LLC – technical advisor for development of vortex tube liquefaction system. Dr. Leachman is a key team member who will participate in transferring the proposed technology to market.

Patrick Adam – Mechanical Engineering PhD student and member of Protium Innovations LLC – Business model development lead – responsible for mapping out a strategy for enterprise development and revenue generation from proposed innovation. Patrick Adam is a key team member who will participate in transferring the proposed technology to market.

Elijah Shoemake – Mechanical Engineering masters student and member of Protium Innovations LLC – technical development lead – responsible for analysis, characterization, and prototype build of proposed innovation. Elijah Shoemake is a key team member who will participate in transferring the proposed technology to market.

Victor Charoonsophonsak – Mechanical Engineering undergraduate student – technical development member – responsible for supporting analysis, characterization, and prototype build of proposed innovation.

Hannah Raine – Mechanical Engineering undergraduate student – technical development member - responsible for supporting analysis, characterization, and prototype build of proposed innovation. Previous internship with an electric utility provides her with insight from an industry perspective.

Travis Woodland – business and IP mentor – responsible for assisting in business model development and ensuring compliance with University IP policies. Travis Woodland is a key team member who will participate in transferring the proposed technology to market.

Plug Power – industry partner – current supplier of hydrogen fuel cell powered material handling systems that is interested in potential use of on-site hydrogen liquefaction using proposed technology.

Stratos Fuel – industry partner – current developer of hydrogen fueling stations for FCEVs is interested in partnership to develop prototype hydrogen fueling station designed at WSU.