Deliverable Report

Power-to-Gas – Hydrogen Leakage Implications

Purpose:
GridEd Undergraduate Design Project Report

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I. Introduction

Growing concerns for the environmental and societal impacts such as air pollution, water contamination, and depletion of natural resources that arise from use of fossil fuels, and an expected global energy demand increase of 89% between 2012 and 2041, has led to major global efforts to accelerate the integration of renewable energy resources with existing power grids [1]. The USEIA expects the total renewable share of electricity generation will increase from 22% in 2012 to 29% in 2040, making renewables the fastest-growing electricity generation resource [1].

Governments around the world have attempted to address these concerns by passing significant climate legislation in recent years. The State of California's impressive leadership in advancing and implementing renewable energy technologies will be reflected in the next 30 years as the state has some aggressive energy and climate goals to meet including: (1) Generate 50% of total electrical energy from renewables by 2030; (2) Generate 100% of its energy from renewables by 2045; (3) Reduce greenhouse gas emissions to 1990 levels by 2020 [2] [3]; (4) Build all new homes to achieve zero-net-energy by 2020. Additionally, Germany has adopted an ambitious *Energiewende*, with a long-term goal to establish a future in Germany that is more "secure, environmentally friendly, and economically successful [4] ." As part of its transition to a more sustainable future, Germany has set similar goals: (1) Source at least 40 to 45% of its energy from renewables by 2025; (2) Source 80% by 2050; (3) Reduce greenhouse gas emissions by 40% from 1990 levels by 2020 [4].

While such goals are impressive, the unpredictable, intermittent, and uncontrollable nature of solar and wind energy generation presents significant challenges for utilities and grid operators. Insufficient energy storage and operational limitations on the grid's flexibility can lead to curtailment and over generation, limiting the amount of renewable power that can be introduced into the grid. These challenges will only be exacerbated with higher levels of renewable energy generation, making large scale and seasonal energy storage critical for successful energy management and for ensuring the highest penetrations of renewable energy.

Power-to-Gas (P2G) has been proposed as an energy storage solution to the challenges that arise from intermittent renewables and the mismatch between the availability of renewable energy and the demands of the electrical grid. The concept of P2G entails converting otherwise curtailed renewable energy to a gaseous fuel (hydrogen) through electrolysis. One of the main advantages of using gas as an energy storage medium is that energy storage capacity can be scaled independently from power capacity, unlike batteries [5]. P2G is also more cost-effective than Lithium-ion ion batteries and more geographically flexible than pumped hydro and compressed air, which are the two main storage technologies for large capacity systems [6] . Finally, P2G is a multi-system solution that also has potential to contribute to the goals of reducing greenhouse gas emissions [7] especially if hydrogen (H_2) is able to replace fossil fuels across the energy consumption sector (i.e. in vehicles and in the natural gas grid). The main drawback to P2G is that it is a relatively new concept that has not been as thoroughly explored as other storage technologies, i.e. most of the P2G pilot plants have only been operated for a short time as stand-alone systems, and there is limited long-term experience [9]. In addition to low round trip efficiencies and high costs [13], the unique features of H2 (flammability limits, diffusivity, density, viscosity, molecular weight) present a significant challenge to further developing P2G.

H_2, the immediate gaseous fuel that is produced from P2G, has with many proposed end uses including: (1) Direct injection in the natural gas (NG) grid at a grid-compatible gas mixtures; (2) Immediate storage in pressure tanks for applications that require H2 such as industrial processes; (3) Conversion of H_2 to methane (CH4) using CO2, where the CH4 can be subsequently fed into the NG grid, as renewable CH4, in unlimited quantities [8]; (4) Electricity generation with fuel cells or internal combustion engines [9]. Direct injection of renewable H_2 into the NG grid would result in significant environmental, operational and economic benefits for the P2G process since H2 is a clean energy carrier and the immediate product of P2G (no chemical conversion energy loses). If H_2 is directly injected to the grid, it can decarbonize part of the NG grid and transform it into a storage and distribution medium for renewable and clean fuel.

The advancement of H_2 storage and generation technologies is essential to achieving the full benefits of the P2G concept. The full benefits of P2G will be realized when H_2 can successfully replace traditional fossil fuels. Despite the potential for H_2 to reduce the carbon footprint of the NG supply system, H_2's unique physical characteristics has caused much concern over the safety of introducing H_2 to the existing NG system. Traditionally, most of the literature that explores gaseous fuel leakage of CH_4 and H_2 has assumed that the differences in chemical and molecular properties between H_2 and CH_4 would lead to increased leakage if H_2 was introduced (i.e. see [10], [11] ,[12], [13]). Though adding H2 to NG infrastructure has potential to affect safety aspects of transmission, distribution, and end use, pipeline durability, pipeline integrity, and end user appliances' performance [14], there is a lack of experimental analyses and observations that quantitatively measure the degree to which leakage is enhanced by adding H_2. Therefore, the goal of this study is to experimentally evaluate the possibility of enhanced gaseous fuel leakage that might be caused by the addition of H_2 to NG infrastructure and appliances.

II. Design and Procedure

Most of the published literature that explores gaseous fuel leakage has assumed that H_2 will leak faster than CH_4. The values range from 1.29 times faster (if the flow through the leak is laminar), 2.89 times faster (if the flow through the leak is turbulent) and 3.15 times faster (if the leakage flow is caused by diffusion) [11]. However, there are very few studies that investigate the possibility of a leak with flow that is not fully developed. The entrance length roughly corresponds to the distance from the entrance where the parabolic velocity profile is no longer changing with distance [15]. The findings from the seminal study of Swain and Swain conducted in 1992 suggest that the many of the leaks in residential fittings may occur through flows that are not fully developed [11]. The findings suggest that if the flows are not fully developed, then the traditional properties used to predict flow rate (such as density, viscosity, molecular weight) may not apply to such flows and that H_2 and CH_4 may leak at similar rates. To further investigate this possibility and to replicate some of their findings, an experimental system was

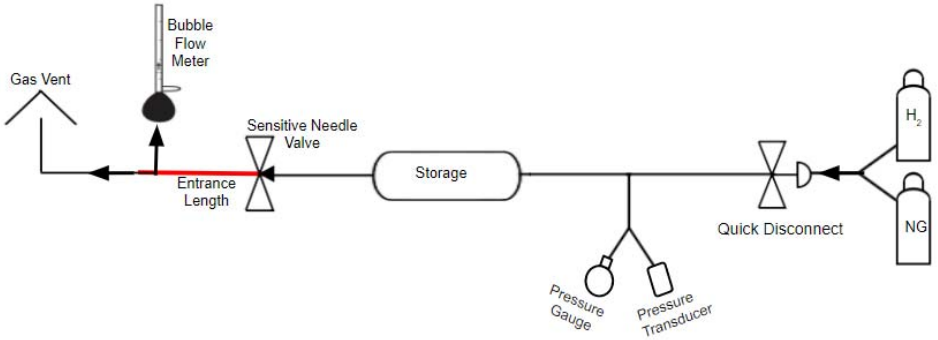

Figure 1: Design of experimental leakage system

built to establish a controlled leak. A sensitive needle valve was used to purposefully create a controlled leak that is in the laminar flow regime. In addition, this valve was swapped, at times, with another larger valve to create a leak in the turbulent flow regime. The entrance length, shown in red in Figure 1, was varied to replicate gaseous fuel leakage that is not fully developed. Each of the three flow regimes was tested with blends of 100% H_2, 100%NG, and 50% H_2 with 50% NG. Various bubble flow meters were used to measure the flow rate of the different gas blends in each of the three flow regimes. The pressure and flow rate were measured to determine the flow regime and leakage rate.

III. List of Equipment Purchased

Following equipment was purchased to build an experimental leakage rig and a gas mixing system. The quantity and unit price (before tax) are listed in Table 1.

Table 1. Description of items purchased for the project

Item Name	Quantity	Unit Price	Total cost
Bubble Meter (10ml)	1	$ 72.40	$ 72.40
Bubble Meter (50ml)	1	$ 79.80	$ 79.80
Bubble Meter (500ml)	1	$ 300.50	$ 300.50
Squeeze Bulb	1	$ 15.10	$ 15.10
Liquid for Bubble Meter	1	$ 12.90	$ 12.90
Thread Sealant	1	$ 4.03	$ 4.03
Stainless Steel Tubing	10	$ 7.99	$ 79.90
Stainless Steel Nut and Ferrule Set	10	$ 2.40	$ 24.00
Stainless Steel Tube Fitting and Reducing Union	1	$ 11.98	$ 11.98
Stainless Steel Double Ended Cylinder	1	$ 79.30	$ 79.30
Stainless Steel Male Plug NPT	1	$ 5.06	$ 5.06
Stainless Steel Swagelok 1/4in Tube Fitting	4	$ 7.34	$ 29.36
Quick Connect Body	1	$ 37.90	$ 37.90
Quick Connect Stem with Valve	1	$ 29.95	$ 29.95
Bonnet Needle Valve (Cv=0.37)	1	$ 68.25	$ 68.25
Low Flow Metering Valve, Vernier handle	1	$ 151.16	$ 151.16
Setra High Pressure Transducer	1	$ 418.20	$ 418.20
Irvine Pipe: Gas Pipes, Regulator, Flex Tubing, Fittings	1	$ 1,370.00	$ 1,370.00
Aluminum Manifold	1	$ 38.98	$ 38.98
Sonic Orifice Size 4,5,7,9	5	$ 20.75	$ 103.75
Sonic Orifice Size 2	1	$ 59.50	$ 59.50
Stainless Steel Pipe Fitting, NPT plug	4	$ 5.35	$ 21.40
Stainless Steel Hex reducing Nipple	2	$ 9.01	$ 18.02
Stainless Steel Tube Fitting Female Connector	15	$ 12.57	$ 188.55
Stainless Steel 3 way valve	3	$ 94.80	$ 284.40

IV. Initial Results

Since the bubble meters and high-pressure pressure transducer did not arrive prior to 12/29/17, limited experiments were completed before 12/29. In the first set of experiments, pure blends of NG and H2 were purposefully allowed to leak through a needle valve with Cv=0.004. The first set of results is presented in Figure 2 below. Note that these results suggest that H2 does indeed leak faster than NG for flows in the fully-developed laminar flow regime. Whereas it took, nearly 300 seconds for H2 to leak 2psig, it took nearly 600 seconds for NG to leak 2psig. Both experiments contained the same amount of gas, in the same enclosed system.

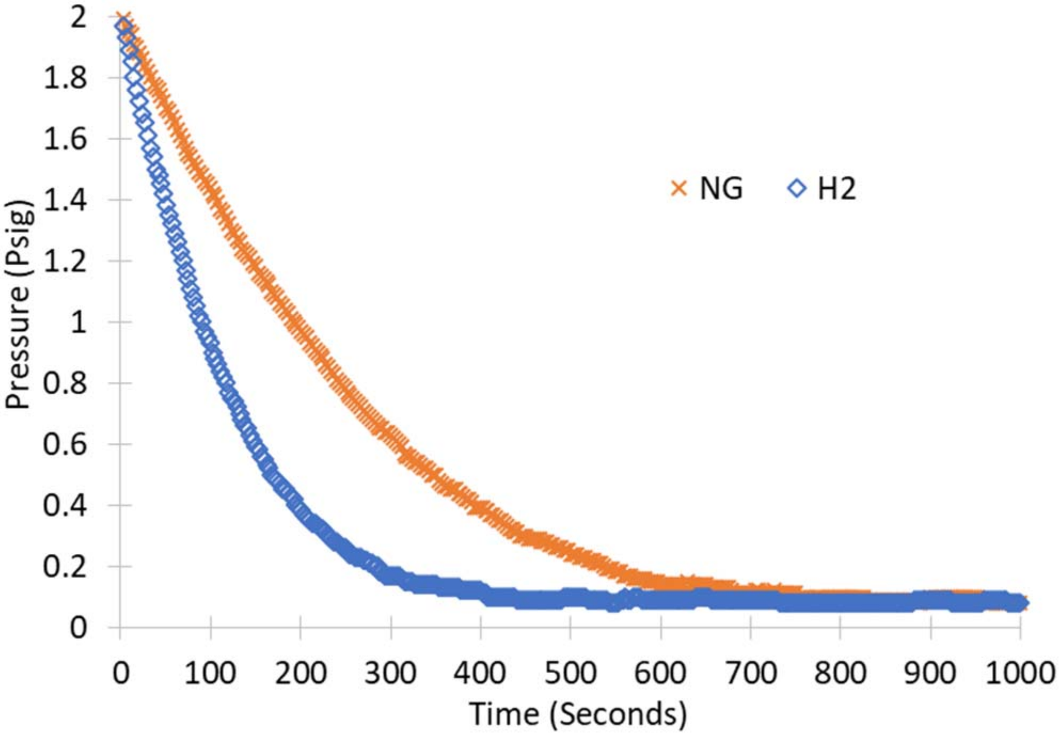

Figure 2: Pressure vs. time of NG and H_2 leaks in the fully-developed laminar leakage flow regime

Some of the data points presented in Figure 2 are presented below in Table 2. From these data points the multiple of time longer that it takes natural gas to leak for the same experimental setup compared to the time it takes for hydrogen to leak the same amount is calculated. Note that the times and pressures presented do not perfectly match. Nonetheless, for the current set of experiments it appears that hydrogen leaks about 1.9 to 2.5 times faster than does natural gas. Note that the conditions established in the current experiments most closely match those of fully-developed laminar flow and that this increased leakage rate falls between that reported by Swain and Swain for fully-developed laminar and turbulent flow.

Table 2. Selected data points measured and calculated multiple of time for how much faster hydrogen leaks compared to natural gas (conditions are for fully developed laminar flow)

Hydrogen		Natural Gas		Multiple of Time
Time (s)	Pressure (psig)	Time (s)	Pressure (psig)	
13.47	1.80	33.42	1.80	2.5
29.43	1.61	66.33	1.61	2.3
47.38	1.41	104.24	1.41	2.2
67.33	1.21	140.15	1.21	2.1
87.28	1.01	185.04	1.03	2.1
112.22	0.81	234.91	0.83	2.1
143.14	0.62	297.76	0.62	2.1
187.03	0.43	373.57	0.43	2.0
262.84	0.23	493.27	0.25	1.9
400.50	0.11	765.59	0.10	1.9

As parts arrive, more thorough experiments will be conducted for each of the gas blends in all of the gaseous flow regimes (e.g., laminar, turbulent, and diffusion controlled). Additionally, future experiments will include an analysis on gaseous fuel leakage through PTFE piping systems.

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