VIII.4 R&D for Safety, Codes and Standards: Hydrogen Behavior

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Project Start Date: October 1, 2003
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Develop a science and engineering basis for the release, ignition, and combustion behavior of hydrogen across its range of use (including high pressure and cryogenic).
- Facilitate the assessment of the safety (risk) of hydrogen systems and enable use of that information for revising regulations, codes, and standards, and permitting hydrogen fueling stations.

Fiscal Year (FY) 2016 Objectives

- Complete construction and commissioning of the cryogenic hydrogen release laboratory.
- Perform initial experimental campaign on cryogenic hydrogen and analyze data such that it can be used for validation of the cold plume model.
- Include additional physics models (e.g., a plume model with an energy balance, improved boundary conditions to the plume model) along with appropriate documentation in the Hydrogen Risk Assessment Models (HyRAM) toolkit.
- Experimentally measure the concentration to velocity spreading ratio for hydrogen.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Safety, Codes and Standards section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(A) Safety Data and Information: Limited Access and Availability

(G) Insufficient Technical Data to Revise Standards

Contribution to Achievement of DOE Safety, Codes & Standards Milestones

This project will contribute to achievement of the following DOE milestones from the Hydrogen Safety, Codes and Standards section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- Milestone 2.13: Develop and validate simplified predictive engineering models of hydrogen dispersion and ignition. (4Q 2015)
- Milestone 4.8: Revision of NFPA 2 to incorporate advanced fueling and storage systems and specific requirements for infrastructure elements such as garages and vehicle maintenance facilities. (3Q, 2016)
- Milestone 2.19: Validate inherently safe design for hydrogen fueling infrastructure. (4Q, 2019)

FY 2016 Accomplishments

- Completed design, construction, and commissioning of the cryogenic hydrogen release laboratory, enabling advanced diagnostic studies of cryogenic hydrogen releases in a unique facility worldwide.
- Released ultra-cold (37 K) hydrogen in the laboratory and studied the laser-spark ignition properties of cold hydrogen.
- Characterized the radiative heat flux emissions of flames from cryogenic hydrogen sources.

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INTRODUCTION

Fire codes govern the required distances between hydrogen sources (e.g., a hydrogen fueling station) and hazards (e.g., ignition sources). Revisions to the fire code distances require justification, which is facilitated by models. These models must be validated with carefully controlled experiments, under relevant conditions, which can include high pressures (10,000 psi) or cryogenic temperatures (20 K). Over the course of this project, experiments have been designed and run to provide validation data for models. Models have been developed and exercised to inform the fire codes. This work has enabled quantitative risk assessments of hydrogen systems, and subsequent reduction of setback distances from high pressure hydrogen sources. Currently, we are focusing on developing a scientific basis for modeling dispersion and flames from cryogenic hydrogen sources. This will provide a technical basis for the revision of fire codes related to liquid hydrogen.

APPROACH

The goals of this work are to develop and validate scientific models to accurately predict hazards and consequences from unintentional hydrogen releases. In this project, we develop one-dimensional and engineering models of hydrogen dispersion and flames that can run quickly on a personal computer. While these models are one-dimensional, they include enough physics (e.g., the effect of buoyancy) to be accurate under a wide range of scenarios. These models are able to characterize the hazards from hydrogen releases and flames and are fast enough that they can be run multiple times and incorporated into a quantitative risk assessment framework. To develop and validate these models, we run carefully controlled experiments. Advanced optical and laser diagnostics are used, along with more conventional diagnostics (e.g., thermocouples) to characterize the dispersion and flame properties of releases, at a lab scale. The temperature, pressure, and orifice of the unignited releases and flames is controlled while characteristics are measured (e.g., concentration, flame temperature, radiative heat flux).

RESULTS

Construction and commissioning of the cryogenic hydrogen release laboratory was realized this fiscal year. This laboratory, shown in Figure 1, enables the study of cryogenic hydrogen releases and flames. Compressed hydrogen is metered and its pressure is controlled within the laboratory, before it flows through a three-stage heat exchanger outside the laboratory. Within the heat exchanger, hydrogen is first cooled by flowing through a coil immersed in liquid nitrogen. A counterflow tube-in-tube heat exchanger, with cold helium vapor, further cools the hydrogen in Stage 2. Finally, in Stage 3, a coil immersed in liquid helium condenses the hydrogen to a liquid, with the helium boil-off acting as the coolant in Stage 2. A single vacuum jacketed line penetrating into the lab facilitates laboratory releases while minimizing the volume of hazardous fluid. A temperature sensor and pressure transducer near an interchangeable nozzle enables careful measurement and control of the boundary conditions for the experiments, which are either unignited, or ignited releases of cryogenic hydrogen. The nozzle is mounted on a three-dimensional translation stage, allowing the release point to move while maintaining diagnostics in a fixed position. The cryogenic hydrogen system can cool hydrogen to a liquid (20–30 K, depending on the pressure), and operate at up to 10 bar, which are characteristic of liquid hydrogen storage tank operating conditions. The nozzles used in the laboratory are small (on the order of 1 mm), and typical cryogenic hydrogen flow rates are on the order of 1 g/s.

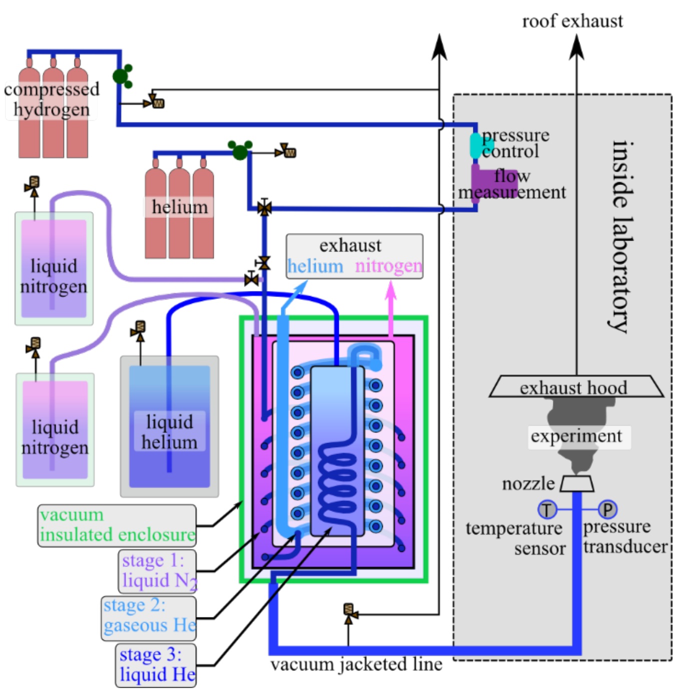

FIGURE 1. Sketch of the cryogenic hydrogen release experiment at the Turbulent Combustion Laboratory, Sandia National Laboratories

The cryogenic hydrogen release laboratory has been used to perform a study on the ignition and radiative properties of jet flames of cryogenic hydrogen. An 8-mm beam from a neodymium-doped yttrium aluminum garnet laser (9-ns pulse duration, 100-mJ/pulse, 532-nm wavelength) was focused, causing a plasma channel, roughly 1 mm in diameter and 4-mm long, to form along the centerline of vertical hydrogen releases. The release point, which began far from the laser-spark, was moved closer to the laser-spark until a sustained jet flame was formed. The cold hydrogen was discovered to ignite further from the release point than warm hydrogen, at a fixed mass flow rate. However, even for cryogenic hydrogen, the ignition distance (the distance between the laser-spark and the nozzle where a jet flame forms), was found to scale with the effective diameter, a relationship that is shown in Figure 2. The effective diameter is the diameter through which the jet mass flow rate, would pass at atmospheric pressure and temperature, to give the same momentum flux as the under-expanded jet at the nozzle exit. This relationship, which has been demonstrated for atmospheric temperature hydrogen releases, was shown to hold true, for cryogenic hydrogen, for the first time in this work.

Radiometers were placed around jet flames of cryogenic hydrogen, to study the heat flux, which is important for determining the hazard to humans and structures, from hydrogen flames. Previous studies [6] have shown that the radiant fraction, which is the fraction of energy released by combustion that is emitted as radiation, scales as a function of the residence time of the flame. We determined this relationship to also be valid for cryogenic hydrogen, as shown in Figure 3. This relationship can be used in a jet flame model, to calculate the radiative heat flux from flames

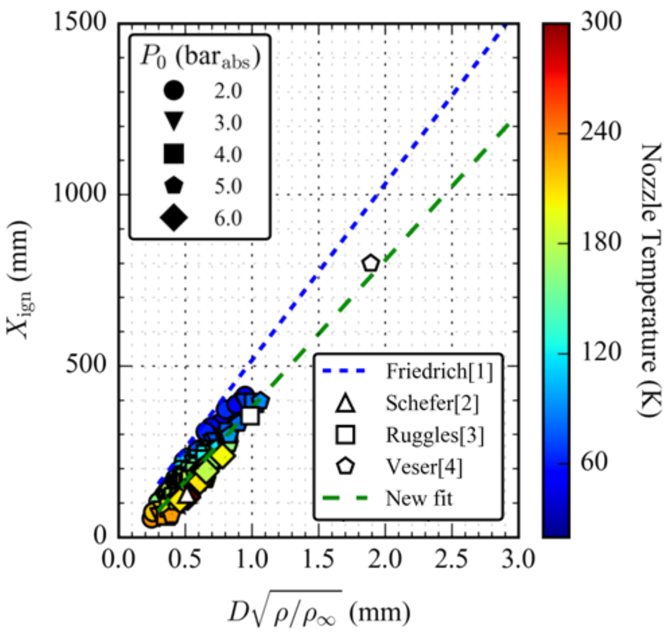

FIGURE 2. Maximum ignition distance as a function of effective diameter, for the cryogenic hydrogen releases in the current study and data from the literature. Blue dashed line shows a correlation from Friedrich et al. [1].

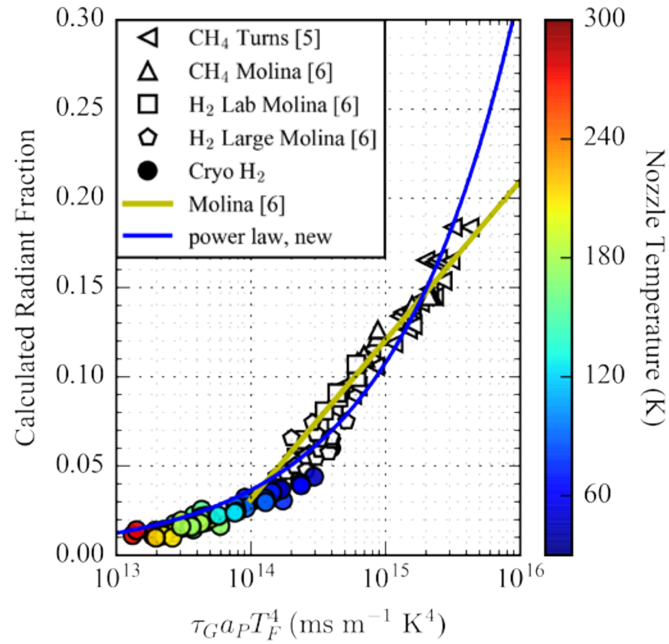

FIGURE 3. Radiant fraction from cryogenic hydrogen jet flames and literate data of flames from atmospheric temperature source gases

of hydrogen from cryogenic or atmospheric temperature sources. The flame length and width were also measured, for cryogenic hydrogen jet flames, using a visible and an infrared camera. As shown by other researchers [8], the flame width was found to be 0.17 times the flame length, for cryogenic and atmospheric temperature flames. The flame length (normalized by the release diameter), shown in Figure 4, was found to scale with the square root of the nozzle exit Reynolds number. This correlation, which was previously shown to be valid for room temperature hydrogen [12], was also shown to hold true for cryogenic hydrogen.

The initial measurements on cryogenic hydrogen ignition, flame radiation, and flame size, using the cryogenic hydrogen release laboratory, have shown that several correlations known to be valid for room temperature hydrogen are also valid for cryogenic hydrogen. These correlations have important modeling and safety, codes, and standards implications. The ignition distance from cryogenic hydrogen sources can now be calculated, which can be used to determine the distance ignition sources should be kept from potential leak points of cryogenic hydrogen systems. The radiative heat flux measurements will help to calculate the human harm distance, and structural damage distance from cryogenic hydrogen jet flames. Additional data from experiments in the cryogenic hydrogen release laboratory and models developed from this data will enable the DOE Milestone 2.19: Validate inherently safe design for hydrogen fueling infrastructure, to be met by its target date of the fourth quarter of 2019.

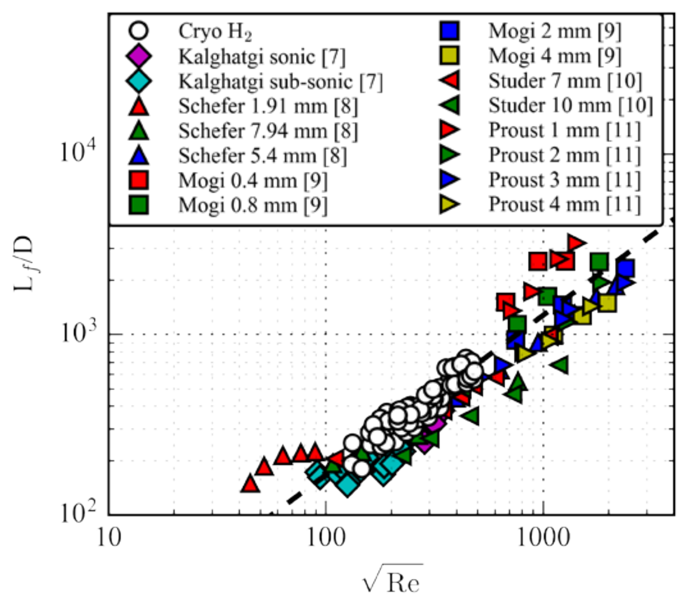

FIGURE 4. Variation of flame length as a function of Reynolds number (Re), for the cryogenic hydrogen releases from the current study, along with data from the literature

CONCLUSIONS AND FUTURE DIRECTIONS

In FY 2016, the cryogenic hydrogen release laboratory was constructed and commissioned. The laboratory was then utilized to measure the distance ignition sources should be kept from cryogenic hydrogen releases, by using a laser-spark to ignite underexpanded hydrogen jets from varied temperature, pressure, and nozzle diameter sources. The properties of flames of cryogenic hydrogen were also studied this fiscal year, including the flame length, width, and radiative heat flux. This data will be used in models of cryogenic hydrogen flames, for example, to calculate the radiative heat flux from cryogenic hydrogen jet flames. This data, and models developed from this data, will be used to inform codes and standards that govern the separation distances for liquid hydrogen.

In the near term, we will be using the cryogenic hydrogen release laboratory to measure the concentration of unignited cryogenic hydrogen releases. To accomplish this, we will be measuring filtered planar laser Rayleigh light scattering. We are currently repairing our laser, so that we can utilize this diagnostic. Concentration data will be used to validate and guide development of a model of cryogenic hydrogen releases. This model will be tied into our quantitative risk assessment toolkit, HyRAM (discussed in the Hydrogen Quantitative Risk Assessment annual progress report), so that it can be used by codes and standards committees and other stakeholders.

In the long term, we plan on designing new experiments to study other phenomena that occur when cryogenic hydrogen is released. These include interactions between liquid hydrogen and the ground (i.e. pooling and evaporation), the effect of the ambient gas (e.g., crosswinds, humidity levels), and the condensation of air and moisture in cryogenic hydrogen. We anticipate that this work will lead to defensible, science-informed separation distances for liquid hydrogen being included in the fire protection safety codes (e.g., National Fire Protection Association 2).

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. *Robert Schefer Memorial Best Paper Award*. Presented to Katrina Groth and Ethan Hecht at the International Conference on Hydrogen Safety (ICHS) for "HyRAM: A methodology and toolkit for QRA of hydrogen systems." Tokyo, Japan, October 2015.

2. Copyright: HyRAM (Hydrogen Risk Assessment Models) v. 1.0. Feburary 17, 2016.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. K.M. Groth and E.S. Hecht. "HyRAM: A methodology and toolkit for Quantitative Risk Assessment of Hydrogen Systems." In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 19–21, 2015.

2. C. San Marchi, E.S. Hecht, I.W. Ekoto, K.M. Groth, C. LaFleur, B.P. Somerday, R. Mukundan and T. Rockward. "Advances in research and development to enhance the scientific basis for hydrogen regulations, codes, and standards." In Proceedings of the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 19–21, 2015.

3. Katrina M. Groth, Ethan S. Hecht and John T. Reynolds. Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.0 technical reference manual. SAND2015-10216, Sandia National Laboratories, Albuquerque, NM, November 2015.

4. Li, Xuefang, Ethan S. Hecht, and David M. Christopher. "Validation of a reduced-order jet model for subsonic and underexpanded hydrogen jets." International Journal of Hydrogen Energy (2015). doi:10.1016/j.ijhydene.2015.10.071.

5. Hecht, Ethan S., Xuefang Li, and Isaac Ekoto (presentation made by X. Li) "Validated equivalent source model for an underexpanded hydrogen jet." Presented at the International Conference on Hydrogen Safety (ICHS 2015), Yokohama, Japan, October 21, 2015. SAND2015-8994 C.

6. Hecht, Ethan S. and Pratikash Panda (presentation). "Validation data for releases from cryogenic hydrogen sources." Presented to the H2 Codes & Standards Tech Team, November 11, 2015 and to the Hydrogen Safety Panel, December 11, 2015. SAND2015-9782 PE.

7. Jay Keller, Laura Hill, Kristian Kiuru, Katrina Groth, Ethan Hecht, Will James, & Thomas Jordan. HySafe research priorities workshop report. Sandia National Laboratories, Albuquerque, NM, SAND2016-2644. Sandia National Laboratories, March 2016.

8. Hydrogen Risk Assessment Model (HyRAM) website. http://hyram.sandia.gov First published January 2016.

9. E.S. Hecht, P. Panda. Liq.uid Hydrogen Behavior Studies. SAND2016-3269 PE. Presented to the Project Technical Panel Kick-off Meeting for 'Spatial Separation Distances for Liquid Hydrogen Storage.' April 2016.

10. E.S. Hecht, P. Panda (presentation). "R&D for Safety, Codes and Standards: Hydrogen Behavior" at DOE FCTO Hydrogen Program Annual Merit Review, Washington, D.C., June 7, 2016.

11. E.S. Hecht, P. Panda (presentation). Liquid Hydrogen Behavior Studies. SAND2016-6149 PE. Presented to the Project Technical Panel Meeting for 'Spatial Separation Distances for Liquid Hydrogen Storage.' June 27, 2016.

12. C. San Marchi, E.S. Hecht, I.W. Ekoto, K.M. Groth, C. LaFleur, B.P. Someday, R. Mukundan, T. Rockward, J. Keller, L. & C.W. James. "Overview of the DOE hydrogen safety, codes and standards program, part 3: Advances in Research and Development to Enhance the Scientific Basis for Hydrogen regulations, Codes and Standards." Accepted for publication in International Journal of Hydrogen Energy, (Accepted July 2016).

13. Katrina M. Groth & Ethan S. Hecht. "HyRAM: A methodology and toolkit for Quantitative Risk Assessment of hydrogen systems." Accepted for publication in International Journal of Hydrogen Energy (Accepted July 2016).

14. P.P. Panda and E.S. Hecht. "Ignition and Flame Characteristics of Under-Expanded Cryogenic Hydrogen Releases." Submitted for publication in International Journal of Hydrogen Energy (Submitted July 2016).

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