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Ignition and flame characteristics of cryogenic hydrogen releases

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ABSTRACT

In this work, under-expanded cryogenic hydrogen jets were investigated experimentally for their ignition and flame characteristics. The test facility described herein, was designed and constructed to release hydrogen at a constant temperature and pressure, to study the dispersion and thermo-physical properties of cryogenic hydrogen releases and flames. In this study, a non-intrusive laser spark focused on the jet axis was used to measure the maximum ignition distance. The radiative power emitted by the corresponding jet flames was also measured for a range of release scenarios from 37 K to 295 K, 2–6 bar_{abs} through nozzles with diameters from 0.75 to 1.25 mm. The maximum ignition distance scales linearly with the effective jet diameter (which scales as the square root of the stagnant fluid density). A 1-dimensional (stream-wise) cryogenic hydrogen release model developed previously at Sandia National Laboratories (although this model is not yet validated for cryogenic hydrogen) was exercised to predict that the mean mole fraction at the maximum ignition distance is approximately 0.14, and is not dependent on the release conditions. The flame length and width were extracted from visible and infra-red flame images for several test cases. The flame length and width both scale as the square root of jet exit Reynolds number, as reported in the literature for flames from atmospheric temperature hydrogen. As shown in previous studies for ignited atmospheric temperature hydrogen, the radiative power from the jet flames of cold hydrogen scales as a logarithmic function of the global flame residence time. The radiative heat flux from jet flames of cold hydrogen is higher than the jet flames of atmospheric temperature hydrogen, for a given mass flow rate, due to the lower choked flow velocity of low-temperature hydrogen. This study provides critical information with regard to the development of models to inform the safety codes and standards of hydrogen infrastructure.

Introduction

Widespread hydrogen use as an alternative fuel for vehicles will require significant infrastructure investments to accommodate increased bulk transport, delivery, and storage of hydrogen. Due to the high density of hydrogen in its liquid phase, fueling stations that store cryogenic hydrogen have been shown to be economically favorable in a future hydrogen economy [1]. The desire to site hydrogen fueling infrastructure for Fuel Cell Electric Vehicles (FCEV) in urban and suburban areas drives an interest in placing bulk cryogenic hydrogen

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storage in space-constrained sites. This storage requirement contrasts with traditional industrial uses of flammable cryogens, for which the safety codes were developed, that are not as space-constrained and can accommodate large safety separation distances. Liquid hydrogen bulk storage separation distances from the current, 2016 edition of National Fire Protection Agency Hydrogen Technologies Code (NFPA 2) [2] for lot lines, building openings or air intakes are in some cases more than twice as large as similar bulk gaseous storage systems. Safety for hydrogen infrastructure is of utmost importance, but the current prescriptive liquid hydrogen separation distances are based on subjective expert opinion rather than physical models, and thus may be overly conservative.

Codes and standards development that governs the storage and transport of liquid hydrogen requires a thorough understanding of release and dispersion characteristics, along with flammability and radiation heat transfer over a range of realistic scenarios and environmental conditions [3]. It is also important to consider specific activities when developing codes and standards, such as repeated fuel transfer connections being made and broken. Most hydrogen releases are expected to be highly turbulent and heavily influenced by buoyancy. Cryogenic hydrogen dispersion can be affected by flashing, multi-phase flows, heat transfer, pool formation, ambient conditions (e.g., temperature, humidity, wind), ground effects, and obstacles/barriers. Extreme cold temperatures can also condense or even freeze ambient air during spills, which differentiates these releases from those of liquid natural gas and can result in unique hazards that likewise need to be understood [4,5]. A review of hydrogen system safety knowledge by Kotchourko et al. [6] includes a detailed discussion of liquid hydrogen systems. Several research priorities and knowledge gaps were identified to enable accurate modeling of liquid hydrogen releases for safety analyses. These include two-phase releases, dispersion of cryogenic and LH_2 in enclosures, physical properties of LH_2, effect of turbulence and, buoyancy on heat transfer between cold hydrogen and ambient air and experiments that can provide a closure to these issues. Hall et al. [7], reported experimental studies to establish the severity of an ignition from a release of $LH_{2,}$ with spill rates consistent with a transfer hose operation. Based on the radiation heat flux measurements they created a safety distance guide which only corresponds to their hydrogen spillage rate. While these and several other large scale studies have looked at the pooling and vaporization of hydrogen [4–8], these experiments are sparsely instrumented with poor control of some boundary conditions. Accordingly, there is the risk that the use of improperly validated models to establish safety envelopes could be detrimental to the emergence of hydrogen as a transportation fuel.

In a controlled laboratory conditions, Friedrich et al. [9] performed release and combustion experiments for cryogenic hydrogen jets with release temperatures between 34 and 65 K and pressures from 0.7 to 3.5 MPa in the ICESAFE (Integrated Cable Energy Safety Analysis Facility and Equipment) facility located at the Karlsruhe Institute of Technology. Hydrogen concentration decay rate measurements preserved the linear dependence when plotted against a density-scaled release diameter. For ignited cryogenic hydrogen jets, the operation states for three possible flame modes were schematically mapped: 1) ignition with flash-back to the release nozzle followed by a stable jet flame, 2) a stable lifted flame without flash-back, and 3) a transient burn with subsequent blow-off. For the jet flames examined, no overpressure or noise hazards were observed. Outside of these experiments, there is a dearth of data in well-characterized environments. Thus, experimental data from well-controlled experiments with high-fidelity diagnostics are necessary to generate parametric databases that can be leveraged for model development and validation [10].

The goal of this work is to advance the scientific understanding of the thermo-physical characteristics of cryogenic hydrogen releases and flames to the point where codes and standards can be informed by the physics of these phenomena. A cryogenic hydrogen release facility was designed, constructed and used in this work to simulate leak scenarios from a liquid hydrogen storage system. The experimental facility was designed for a controlled, steady-state release at fixed pressure and temperature. In future experiments, the dispersion properties will be characterized using advanced laser diagnostics such as filtered planar laser Rayleigh scatter, capable of accurate instantaneous hydrogen concentration measurements, and complementary flow velocity measurements using particle image velocimetry. Within the laboratory, similar experiments have been performed on high-pressure gaseous hydrogen releases [11–14], leading to modifications of NFPA 2.

As discussed by LaChance et al. [15], the radiant heat flux from a jet flame is a critical parameter that governs the deterministic separation distance (or the hazard distance) to prevent harm during an accident scenario. An understanding of the ignition distance, which is related to the local fuel mass fraction, can inform other separation distances, such as the distance hydrogen infrastructure should be kept from ignition sources (e.g., power lines). In the present study, cold (as low as 37 K) hydrogen releases formed under-expanded jets that were subsequently ignited with the help of a laser generated spark. A maximum ignition distance (X_{ign}), which is defined as the maximum distance from the nozzle exit at which a laser spark causes upstream flame propagation leading to a sustained jet flame, was measured. The radiative power from the sustained turbulent diffusion jet flames was measured using radiometers. We have developed correlations such that the flow variables can be used to calculate the maximum ignition distance and radiant heat flux from ignited flames of cryogenic, under-expanded hydrogen jets.

Cryogenic hydrogen release experimental system

Cryogenic hydrogen release experiments were performed at the Turbulent Combustion Laboratory at Sandia National Laboratories. Liquid hydrogen tanks store hydrogen at fairly low pressure (usually 3–5 bar), at the saturated liquid temperature (28 K at 6 bar_{abs} and 23 K at 2 bar_{abs}); the cryogenic hydrogen release experiment was designed to simulate these conditions. A sketch of the cryogenic hydrogen release experimental system is shown in Fig. 1. During experiments, gaseous hydrogen flowed into the laboratory through a Tescom 44-3200 series pressure regulator followed by a Teledyne-

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