Demonstration of Hydrogen Combustion Properties

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Introduction

The Hydrogen Flame Demonstration project encompasses the design, fabrication, and usage of a pressure vessel system with the goal of demonstrating the hazardous flammable properties that are associated with gaseous hydrogen. This project was completed as a part of a 16-week internship at the NASA White Sands Test Facility in Las Cruces, New Mexico during the spring of 2022. As the interest in technologies using hydrogen as a fuel, or otherwise, increases, informing and setting 'best practices' for the use of pressure systems containing hydrogen becomes increasingly necessary. Gaseous hydrogen is highly flammable with the presence of air or oxygen. Since the minimum ignition energy (MIE) of a stoichiometric mixture of hydrogen with air is exceptionally low at 0.017 mJ[1], the lower flammability limit of hydrogen in air is only 4% by volume[2], hydrogen flames in air are invisible to the naked eye, and the size of the hydrogen molecule is small which makes it prone to leakage, common failure modes of hydrogen include deflagration, detonation, and non-visible flames. However, the technologies associated with hydrogen as a fuel are promising and could be the solution to climate change issues. To unlock the potential of hydrogen-based technology, researchers, engineers, and handlers that associate with such technologies should be informed and design for the hazards involved. This project demonstrated the characteristics of a hydrogen flame with in-person demonstrations, high quality video of the demonstrations, and will serve as the foundation of future experiments to investigate hydrogen flame properties such as auto-ignition conditions in collaboration with the U.S. Department of Energy.

Project Objective

The hydrogen group at the NASA White Sands Test Facility identified the need to create a hydrogen demonstration pressure vessel system and operate the system for the purposes of updating the NASA hydrogen safety course to inform public and private partners about the hazards associated with hydrogen gas and the 'best practices'. This pressure vessel system needed to be designed so that an open hydrogen flame could be ignited for a sustained period of time in a manner that demonstrates the safe use of hydrogen. The technical specifications for the physical demonstration pressure vessel system were compiled as a result of an investigation of hydrogen properties, internal NASA requirements, internal White Sands Test Facility requirements, discussions with hydrogen subject matter experts, the guidance of internship program mentors, and a NASA internal safety review. Assumptions of use, human factors, and defined engineering specifications are limited to the NASA internal Failure Modes and Effects Analysis (FMEA) and Hazard Analysis (HA). Technical specifications for the hydrogen flame demonstration project are divided into functional specifications and safety specifications. Specifications for safety are generated by ensuring the system is single point failure tolerant by performing an FMEA, and every hazardous risk does not exceed the permissible amount as documented and maintained by a HA. Once the system receives the necessary approvals, the system is to be used as a tool for a hydrogen flame demonstration and be used in auto-ignition experiments. The objective for the demonstration is educate hydrogen system designers and handlers to the properties of a hydrogen flame. Additionally, this system will be the subject of an engineering investigation regarding hydrogen flame ignition properties though a joint effort with NASA and the U.S. Department of Energy.

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System Design

The hydrogen flame demonstration system is a series of a frame, piping, and instrumentation that manages the pressure of the supplied hydrogen from a hydrogen k-bottle. The hydrogen k-bottle is secured in a k-bottle rack which also consists of a nitrogen k-bottle which is used for a purge, leak check and lowers the center of gravity of the system. Downstream of the hydrogen k-bottle is an orifice to limit the flow directly out of the k-bottle. Downstream of the orifice is a regulator that leads to a series of piping that includes a pressure safety valve which leads to a pipe that leads to a T fitting which is 8 feet above the ground. This is the purge line. In series with this line is a manual valve that is used to relieve that section of piping to ambient pressures through the purge line. This section of piping is closed off with a hand valve and leads to the flame vent. The flame vent also has one last hand valve that can be open or closed to modulate the flow of hydrogen for the demonstration. The flame vent is at a 45-degree angle with respect to the ground downstream of the hand valve.

System and Demonstration

The Hydrogen Flame Demonstration System is depicted in Figure 1. At this point, the system is fully constructed, purged with nitrogen, and the leak check procedure has been successfully completed. Figure 2 is a frame from the thermal imaging camera during the hydrogen flame demonstration. The demonstration video shows a side-by-side comparison of the thermal imaging and normal vision. The flame is invisible with normal vision. The video includes the operator putting a straw broom in the flame to show that the flame is there despite the inability to see it. The demonstration video also shows the functionality of the manual valves and regulators on the system. After the demonstration, the system must be depressurized by opening the manual valve on the vent system.

Figure 1: Hydrogen Flame Demonstration System

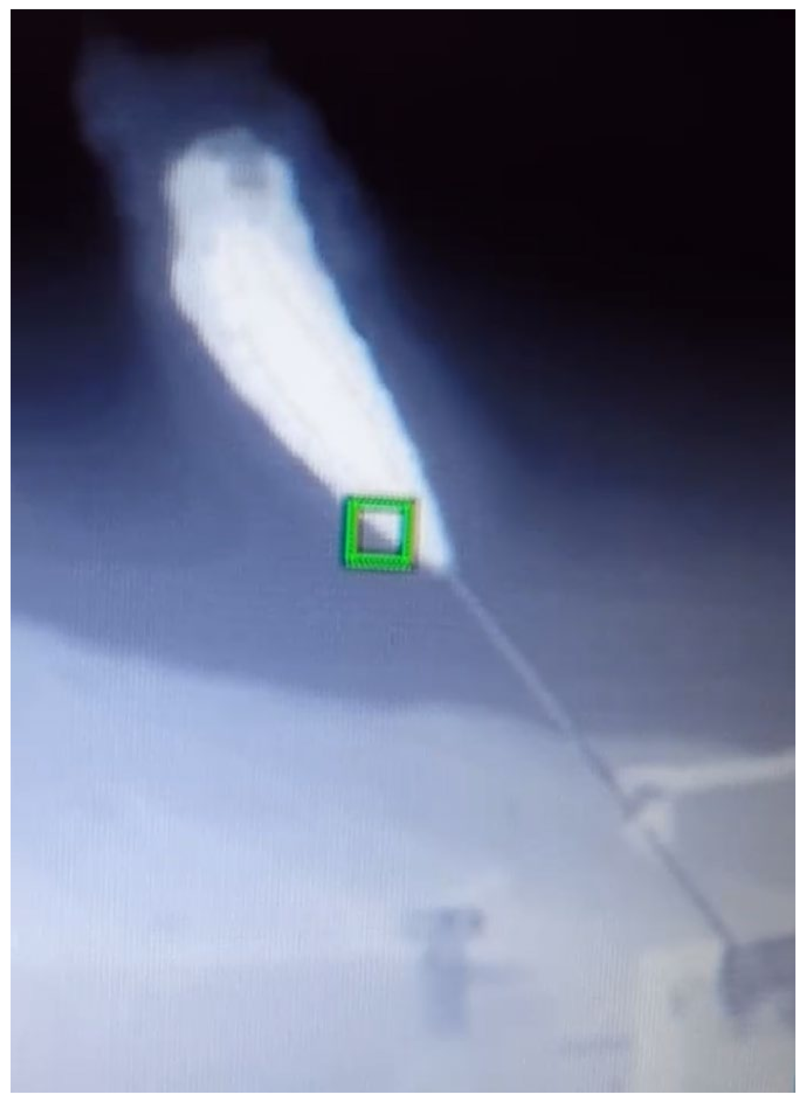

Figure 2: Thermal Imaging of a Hydrogen Flame

Internal NASA Evaluation

The hydrogen flame demonstration system was analyzed by subject matter experts, operating technicians, buildup technicians, pressure vessel system certification contractors, mentors, and safety officers to ensure the system is safe for operation. The primary mechanism for this analysis is the NASA internal safety review which is conducted upon system buildup and is required for system usage. Additionally, the feedback generated from the demonstrations is used as an evaluation. In-person spectators and personnel enrolled in the hydrogen safety course provide feedback through a feedback system that is internal to the hydrogen group at NASA White Sands Test Facility. Here, people provided their overall opinions and educational experience going through the training and demonstration. The project is successful since the hydrogen flame demonstration project passed the internal NASA safety review, the demonstration was completed with no incidents or close-calls, and in-person and virtual spectators to the demonstration provided positive feedback. Hydrogen system designers and handlers have been informed of the hazards of hydrogen and that knowledge will assist in their own projects.

Pressure Vessel System Certification

When designing and constructing a Pressure Vessel System (PVS), the system first must be approved for PVS certification. This process includes creating a process and instrumentation diagram that satisfies internal NASA WSTF constraints such as system grounding, performing a leak check, a nitrogen purge, sufficient structural stability, safe operational instructions, and pressure safety valves where required. Each system component must be certified (as denoted by a red tag) and the complete system must be certified for use. PVS certification included working with multidisciplinary engineers and subject matter experts to ensure all system constraints and safety efforts are completed. The Hydrogen Flame Demonstration System received full certification along with a date of expiration. This authorized the operation of the system in a specific area at WSTF. The PVS certification assisted with the overall safety review which is required to execute the demonstration.

Future Endeavors

The hydrogen flame demonstration video will be used for internal and external educational content regarding the design and usage of hydrogen systems. Additionally, the system will be used for hydrogen experiments such as properties of auto-ignition and conditions for ignition. The U.S. Department of Energy will use this system as a part of an engineering investigation to discover mitigation for hydrogen combustion hazards.

References

[1] Metzler, A.J., Minimum Ignition Energies of Six Pure Hydrocarbon Fuels, NACA Report RM E52 F27 1952

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