INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 39 (2014) 9545–9551

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Intensity calibrated hydrogen flame spectrum

Ellen E. Arens, Robert C. Youngquist, Stanley O. Starr*

Mail-Stop NE-L5, National Aeronautics and Space Administration (NASA), Kennedy Space Center, FL 32899, USA

ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form
14 March 2014
Accepted 5 April 2014
Available online 27 April 2014

Keywords:
Hydrogen flame spectroscopy
Flame spectroscopy
Hydrogen fire detection
Ultraviolet fire detection
Infrared fire detection
Fire detection

ABSTRACT

The detection of hydrogen fires is important to the aerospace community. The National Aeronautics and Space Administration (NASA) has devoted significant effort to the development, testing, and installation of hydrogen fire detectors based on ultraviolet, near-infrared, mid-infrared, and/or far-infrared flame emission bands. Yet, there is no intensity calibrated hydrogen-air flame spectrum over this range in the literature and consequently, it can be difficult to compare the merits of different radiation-based hydrogen fire detectors. In this paper we present an intensity calibrated irradiance spectrum for a low pressure hydrogen flame burning in air from 200 nm to 13.5 microns that varies by more than six orders of magnitude. The results resolve relative intensity errors between spectral bands that appear within the literature. The impact of the measured spectrum on the choice of radiation-based hydrogen fire detectors is discussed.

Introduction

The National Aeronautics and Space Administration (NASA) is one of the largest consumers of hydrogen in the world. The Apollo Program Saturn V Rocket second stage held 70,000 kg of liquid hydrogen, the Space Shuttle External Tank held over 100,000 kg of liquid hydrogen, and the proposed future Space Launch System liquid hydrogen tank will likely exceed these quantities. During the Space Shuttle Program NASA's Kennedy Space Center (KSC) alone purchased approximately 900,000 kg of liquid hydrogen annually all of which had to be transported and stored; and then routed via a cross country line, shown in Fig. 1, on its way to the launch vehicle. Much of KSC's hydrogen infrastructure was constructed in the 1960's and is located near the ocean, a corrosive environment, so both hydrogen leak and hydrogen fire detection have been given serious attention.

Hydrogen fires emit very little visible radiation and are essentially invisible in daylight. In the early years of aeronautics, brooms were held in areas where there might be a fire [1] and even now paper is sometimes taped in locations where a fire may occur to provide a visible signature. During the Apollo program hydrogen fire detection was studied—reference 1 provides a survey of this work—with the result that ultraviolet (UV) detection based fire detectors were placed at the KSC launch pads. It was known that hydrogen fires emit substantial infrared (IR) radiation, but it was difficult at the time to make an IR fire detector that would not false alarm from the sun's emission. However, the ultraviolet region below 280 nm has no solar component, due to absorption by the ozone layer, yet the atmosphere transmits down to 180 nm, creating a transmission window free of solar content. Hydrogen fires have some emission in this 180 nm–280 nm region and very sensitive UV detectors, such as Hamamatsu's

* *Corresponding author*. Tel.: +1 321 867 1829; fax: +1 321 867 1177.
E-mail address: Robert.C.Youngquist@nasa.gov (R.C. Youngquist).
http://dx.doi.org/10.1016/j.ijhydene.2014.04.043

UVTRON® tube, operate in this spectral region, allowing the construction of solar-blind fire detectors.

But these UV fire detectors were not ideal and problems arose during the Space Shuttle program. They required high voltage to operate and had to be enclosed in explosion proof housings. The UVTRON® tubes degraded during operation—requiring frequent calibration—necessitating the construction of a portable hydrogen fire UV simulator [2] to provide fire detector recertification at the pad prior to each launch. In 1984 a hydrogen fire, resulting from an engine cutoff, caused the launch pad fire detectors to alarm, but their large field of view failed to indicate the source or the location of the fire. This led to confusion and a decision to install infrared cameras. Infrared camera technology was nascent at this time and NASA labs sought to develop options to the installed far-IR cameras by demonstrating hydrogen fire cameras that operated in the near IR [3] and in the mid-IR [4]. The large field of view of the UV fire detectors also caused false alarms, primarily from the hydrogen flare stack. Fig. 1 shows this large vertical structure through which liquid hydrogen boil-off flows to be burned, resulting in a 100–200 foot long hydrogen flame billowing at the launch pad at the same time that the hydrogen fire detectors are monitoring specific locations for unwanted fires. Reflections from the flare stack flame off of pad structures have led to numerous false alarms and this has been a perennial problem throughout the Space Shuttle program. Consequently, during this transition period between the Space Shuttle Program and the Space Launch System, modern alternatives, such as multi-spectrum infrared fire detectors, are being evaluated.

Hydrogen fire detection encompass a very wide spectrum, from the deep ultraviolet through the far-infrared, yet, no intensity calibrated hydrogen flame spectrum across this range exists in the literature. There are publications describing the ultraviolet spectrum [5,6], the infrared spectrum [7], and even the visible emission of hydrogen flames [8], but these are rarely intensity calibrated. Of even more concern, some references provide intensity plots showing the ultraviolet spectral peak to be greater than the near-infrared [5] and even the middle infrared [8] spectral peaks. This is incorrect. The ultraviolet irradiance is less than the infrared irradiance, as will be shown below, but in neither Ref [5] or Ref [8] is there sufficient discussion or reference to explain the source of these erroneous spectral plots. Such inconsistencies and lack of information in the literature make it difficult to compare ultraviolet and infrared based hydrogen fire detection approaches.

Experimental configuration

Flame description

Based on the issues highlighted above a decision was made to perform calibrated measurements of the intensity of a KSC 'standard' hydrogen flame from 200 nanometers (nm) in the ultraviolet to 13,500 nm in the far-infrared. The KSC standard hydrogen flame is generated by flowing 20 L/min of hydrogen through a 0.16 mm (1/16th inch) diameter orifice, resulting in a flame that is about 60 cm (2 feet) high and 15 cm (6 inches) wide (as viewed in the infrared). This is indicative of the type of low pressure flame that might result from a leak at a KSC launch pad. This flame was placed 4 m (13 feet) in front of the spectrometer in order to ensure that the entire flame was within the spectrometer's field of view. We chose to measure the entire spectral irradiance produced by all portions of the flame and not the spectral radiance generated by specific regions of the flame, since most flame detectors have a wide field of view and will see the entire flame. All testing was performed outside during night hours in order to minimize background radiation from the sun and to minimize wind induced motion of the flame.

The spectrum of a hydrogen flame will vary with pressure, size (i.e. flow rate), and mixing so we took care to ensure that the flame was generated identically for each set of measurements. We used high purity hydrogen, 99.999 percent pure, with less than 3.0 ppmv water, less than 2.0 ppmv oxygen, and less than 1.0 ppmv of carbon dioxide, carbon monoxide, and methane. We did not measure the spectrum from larger or smaller flames, but expect the relative spectrum of low pressure atmospheric hydrogen flames to vary weakly with size based on the optical depth of the flame at different wavelengths. Strongly absorbing wavelengths, such as those in the 2400–2900 nm range, are primarily surface emission and the irradiance at these wavelengths will vary with the flame area while more weakly absorbing bands are emitted from throughout the flame and will exhibit a volume dependent irradiance.

Fig. 1 – Liquid hydrogen is carried to the launch pad through a cross country line from an 850,000 gallon (3,200,000 L) storage tank. The vertical column is the flare stack where hydrogen boil-off is burned. The Atlantic Ocean is in the background.