Fuel Leak Simulation

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Abstract

This work effort was conducted to serve two purposes. The first was to produce a video comparing the severity of a hydrogen and gasoline fuel leak and ignition. The second was to determine why the hydrogen flames videotaped were so easily visible. The videotape was completed and lasted approximately 3.5 minutes. The flame visibility was due to naturally-occurring particulate matter in the air. The particulate matter contained sodium, which enhances flame visibility.

Introduction

This work has been conducted to fulfill two objectives. They are:

1. Produce a 3.5 minute video comparing the severity of ignition of single failure mode fuel leaks from a hydrogen or gasoline fueled vehicle.
2. Determine why the hydrogen flames videotaped in previous experiments are so easily visible.

Previous experiments on the combustion of a hydrogen leak from a hydrogen-powered automobile have shown that the hydrogen diffusion flame has a yellow color. This is not consistent with a hydrogen diffusion flame entraining a relatively pure nitrogen/oxygen mixture and suggests the presence of an unknown impurity or impurities. The chemistry associated with a turbulent hydrogen/oxygen/nitrogen diffusion flame is well characterized, producing super-equilibrium concentration levels of the hydroxyl radical, together with hydrogen atoms in rich parts of the flame and oxygen atoms in lean areas. None of these species produces an emission signature in the visible portion of the spectrum. The object of this work was the characterization of the spectral content of the emission from such a diffusion flame.

Video of Fuel Leakage and Ignition

The video was completed on schedule and was shown publicly March 5, 2001 at the NHA meeting in Washington. Eight frames from the video are included in the Appendix. At the NHA meeting, an oral narration was given with the video. The video simply depicts the single failure mode leakage and ignition of fuel from the two vehicles but, as of yet, has no narrative. It is felt a narrative describing in detail the accident scenarios for the two vehicles and perhaps some additional video footage of hydrogen fuel line leakage should be added before the video is presented to the public.

The gasoline and hydrogen single failure mode accident scenarios were as follows:

Gasoline leakage: the fuel line of a gasoline fueled vehicle was punctured with 1/16 inch diameter hole and gasoline leaks out of the fuel line under the middle of the car. During the 3.5 minutes of videotaping, the vehicle leaks five pints of gasoline (approximately 70,000 BTU). Several events of interest occur including a deflagration of gases inside the vehicle interior and trunk, ruptures of the vehicle's tires, and an unrestrained release of coolant from the air conditioner. These should be described in the narration.

Hydrogen leakage: the hydrogen-fueled vehicle was designed consistent with existing manufacturer specifications. They include sensors for hydrogen that activate shut-off solenoids in the hydrogen tank, and computer programming to shut off fuel supply if fuel flow exceeds that used by the fuel cell, or fuel flow delivered drops by a predetermined amount. In light of the additional safety precautions designed into hydrogen-fueled vehicles the most severe single failure mode accident scenario is that of hydrogen leakage at the tank pressure release device (PRD) causing a standing flame, which in turn causes the PRD to allow all the hydrogen in the tank to escape in 100 seconds. During the video, the hydrogen vehicle leaks 3.4 pounds of hydrogen (approximately 175,000 BTU).

For hydrogen to leak under a hydrogen-powered vehicle in amounts that would produce a severe accident four failures, must occur. They are:

1. Fuel line or component sealing failure.
2. The hydrogen sensor system that detects hydrogen and shuts off hydrogen flow must fail.
3. The tank mounted excess flow valve required by manufacturers specifications must fail.
4. Flow sensing computer programs, that compare hydrogen flow to hydrogen consumption of the fuel cell, must fail.

Other failures could disable some of the above-mentioned systems but no single failure mode could produce a severe hydrogen leak under the vehicle.

Conclusions Concerning Video

The damage to the gasoline-powered vehicle was severe. The hydrogen-powered vehicle was undamaged. The maximum surface temperatures measured on the hydrogen-powered vehicle

were 117°F on the rear window glass and 67°F at the rear tray (between the rear window and rear seat).

The 3.5-minute video of the accidental leakage and ignition of a hydrogen- or gasoline-powered vehicle should have a narration added to describe their respective accident scenarios and events occurring in the video. Additionally short (5-second) video segments should be added to show the diminished severity of hydrogen leakage and ignition when interrupted by one of the onboard safety systems.

Spectral Analysis of Hydrogen Flames

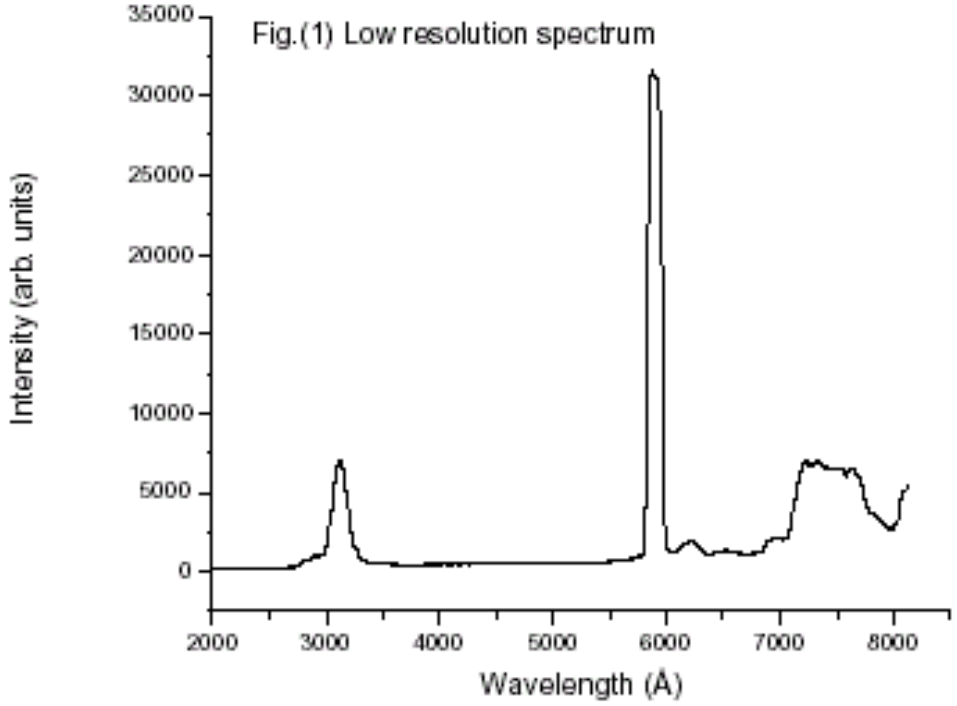
The hydrogen flames were subjected to spectral analysis to investigate flame visibility. The cause of enhanced hydrogen flame visibility was found to be naturally-occurring particulate matter, containing sodium, which was entrained into the flame. This has occurred during all the tests conducted over the last 30 years. The following is a description of the spectral analysis.

The experimental setup consisted of two optical multichannel analyzers (OMA) based on 1024 element diode arrays that were mounted on spectrographs. In a conventional single element detector/spectrometer system, one obtains a spectrum by tuning a diffraction grating and observing the light intensity at the detector as a function of wavelength. In an OMA system, the diffraction grating is fixed and the diode array is placed in the output focal plane of the spectrograph. Hence the OMA collects an instantaneous snapshot of a complete spectrum. In these experiments two EG&G OMA's were used. The unintensified array was mounted on a 1/4 m spectrograph that contained a 150 grooves/mm grating. This low-resolution system had a spectral width of approximately 6000 Å allowing it to cover the ultraviolet, visible and near infrared. The intensified array was mounted on 3/4 m spectrograph containing a 2400 grooves/mm grating. This system had a spectral width of approximately 160 Å with a resolution of 0.6 Å. Fused silica lenses were placed in front of the entrance slits to attempt to image a relatively narrow portion of the hydrogen diffusion flame. The lenses and spectrographs were placed approximately 1 meter from the flame. The lenses and spectrographs were adjusted by focusing onto a small calibration lamp to ensure that both systems were imaging the same region of the flame. Spectra were obtained simultaneously using both systems.

Results and Discussion

Figure (1) shows a typical low-resolution spectrum of the flame and is not corrected for the spectral response of the spectrograph and diode array. It is clear however, that three features dominate the spectrum:

1) a broad peak in the ultraviolet at ~ 3000 Å.
2) a narrow peak at ~ 5890 Å.
3) a broad peak in the near infrared between 7000-8000 Å.

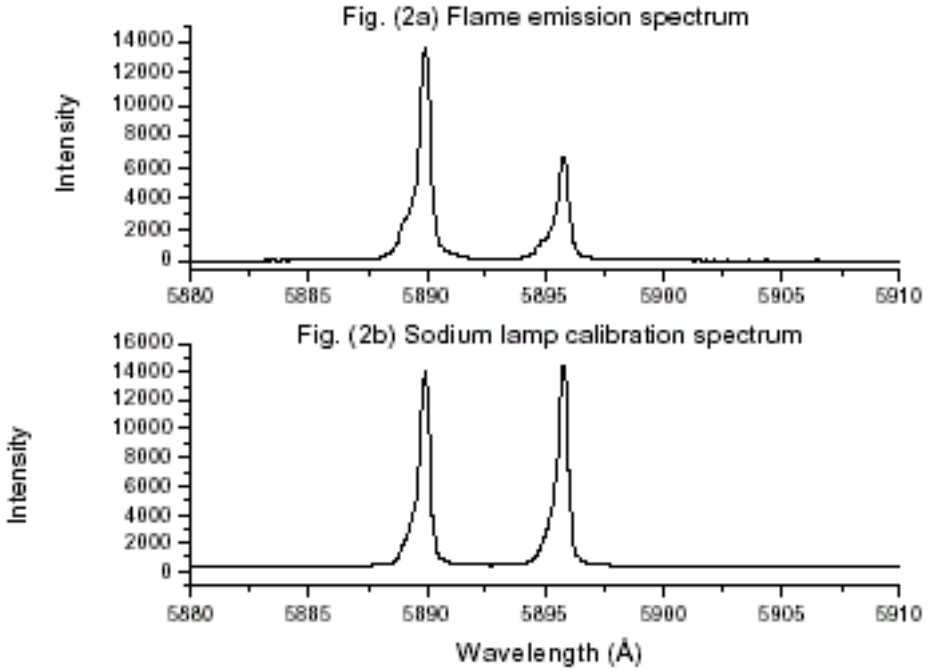


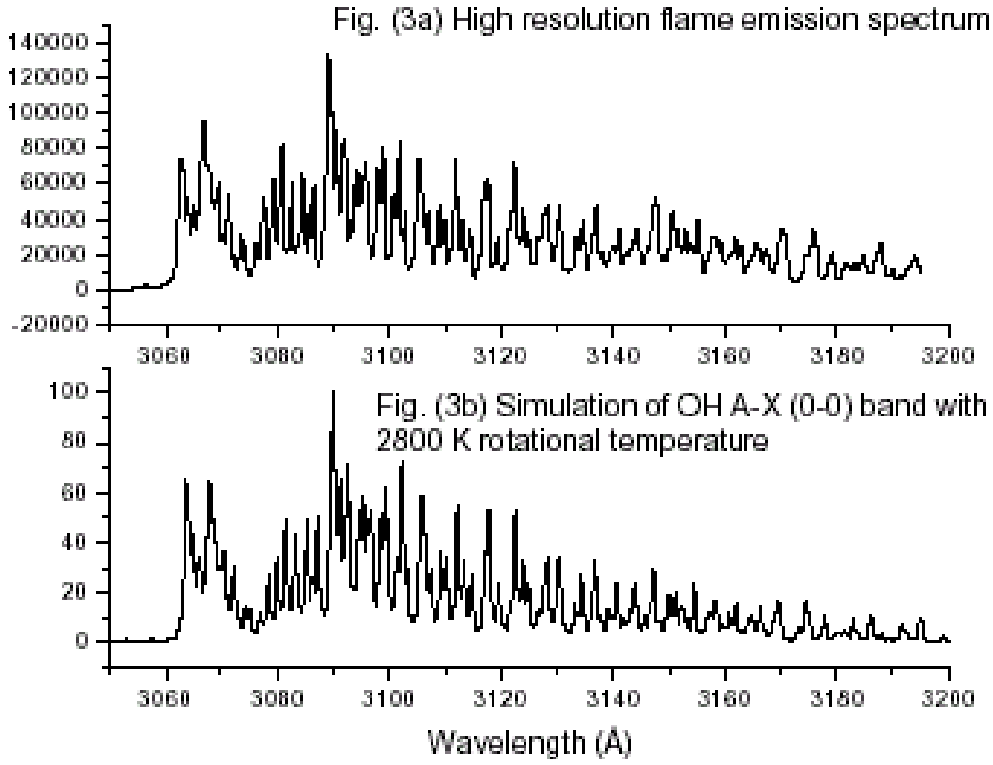
There is an additional signal that lies above the background noise. Its integrated intensity is small compared with the main features and no clear spectral signature scan be identified at this spectral resolution.

Figure (2a) shows a high-resolution spectrum of the 5890 Å feature taken with the 3/4 m spectrograph. Figure (2b) shows the spectrum of a high-pressure sodium lamp taken under identical conditions with the lamp in place of the flame. The high-resolution spectrum demonstrates unequivocally that the dominant flame emission is due to sodium D line emission. The characteristic D line doublet is due to emission from the excited ^2P state and consists of the D1 line due to the ($^2P_{1/2}$ - $^2S_{1/2}$) transition at 5895.93 Å and the D2 ($^2P_{3/2}$ - $^2S_{1/2}$) transition at 5889.96 Å.

Figure (3a) shows a high-resolution spectrum of a portion of the 3000 Å feature. It can be seen that, in contrast to the sodium D lines we have a complex multi-line spectrum. This is characteristic of the spectrum of a simple diatomic or polyatomic molecule and the relatively open structure suggests a hydride. The strong emission spectrum of the OH A $^2\Sigma$-X ^2D (0-0) band lies in this region. This emission is characteristic of H_2/O_2 flames and has been extensively observed and characterized. A quantitative identification requires a computer simulation of the spectrum. Figure (3b) shows a simulation of the OH A-X (0-0) emission spectrum assuming a rotational temperature of 2800 K and a spectral resolution of 0.6 Å. The simulation clearly identifies the experimental feature as being due to OH. We have not attempted to identify the broad infrared spectral feature. Several sets of high and low-resolution spectra were obtained and this involved relighting the flame several times. It is an extremely turbulent diffusion flame

but nevertheless the degree of reproducibility of both the low and high-resolution spectra was remarkable.





These results demonstrate that the dominant spectral feature in the visible region of the spectrum is due to sodium D line emission. This is due to particulate matter containing sodium that is entrained into the flame. The results also demonstrate that we can obtain high-resolution spectra of the OH radical, which may serve as an important flame diagnostic particularly of flame temperature. If the sodium emission is due primarily to thermal excitation, then the brightness of the sodium D line emission will depend on the diffusion flame temperature.

Conclusions Concerning Spectral Analysis

The cause of enhanced hydrogen flame visibility was entrained particulate matter that contained sodium that was naturally occurring in the air.

Appendix (Frames From Video)

Photo 1 - Time: 0 min, 0 sec - Hydrogen powered vehicle on the left. Gasoline powered vehicle on the right.

Photo 2 - Time 0 min, 3 seconds - Ignition of both fuels occur. Hydrogen flow rate 2100 SCFM. Gasoline flow rate 680 cc/min.

Photo 3 - Time: 1 min, 0 sec - Hydrogen flow is subsiding, view of gasoline vehicle begins to enlarge

Photo 4 - Time: 1 min, 30 sec - Hydrogen flow almost finished. View of gasoline powered vehicle has been expanded to nearly full screen

Photo 5 - Time: 2 min, 20 sec - Frame prior to interior deflagration.

Photo 6 - Time: 2 min, 20 sec - Deflagration in the interior, following frame shows flames exiting around edges of trunk lid.

Photo 7 - Time: 2 min, 40 sec - Frame prior to driver's side rear tire rupture.

Photo 8 - Time: 2 min, 40 sec - Driver's side rear tire rupture sends debris out the passenger side of the vehicle.