Application of Hydroxyl (OH) Radical Ultraviolet Absorption Spectroscopy to Rocket Plumes

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ABSTRACT

A spectrometer system was constructed for measurement of transient species in flames by absorption of ultraviolet radiation. The output of a xenon arc lamp was used as the source of radiation, which was focused through the flame and onto a monochromator equipped with an intensified silicon diode array detector. The system was used to measure absorption by hydroxyl (OH) radical around 306 nm in the plume of a hybrid rocket motor. Hydroxyl terminated polybutadiene (HTPB) was used as the fuel and gaseous oxygen as the oxidizer. The experimental spectra were analyzed by comparison with known vibrational and rotational lines using a multi-parameter curve-fitting program. OH radical concentration and temperature profiles of the rocket plume are presented along with details of the spectrometer specifications.

Keywords: absorption spectroscopy, hybrid rocket motor, combustion diagnostics

Introduction

By increasing the understanding of the combustion of hybrid rocket fuels, new and improved fuels can be developed. Because burning is rapid, complex, and variable, investigative methods must be fast and non-intrusive. This work is an adaptation of techniques developed by Vanderhoff, et al. in which absorption of ultraviolet and visible light was used to detect and measure species involved in solid propellant combustion at modest pressure.[1–4]

A hybrid rocket motor employs a solid fuel grain through which the oxidizer is flowed. It combines some of the advantages of a liquid-propellant motor (start-stop-restart and throttle capabilities, and safety) with some of the advantages of solid-propellant motors (less plumbing and higher propellant density).

It is commonly accepted that hybrid rocket fuel burns according to the model shown in Figure 1.

In the boundary layer between the fuel and oxidizer flow, combustion takes place at the intersection of the vaporized fuel flow and oxidizer. This combustion zone is formed within the momentum boundary layer and is the source of the heat flow to the surface to maintain fuel vaporization. The flame front is located at about the point where stoichiometric fluxes of fuel and oxidizer result and the thickness of the zone is dependent on the chemical reaction rates. Depending upon the configuration of the exit nozzle and the amount of turbulence, the respective zones of the boundary layer may extend far enough beyond the end of the rocket to be accessible to remote spectral studies.

Experimental

Spectrometer development work was performed at Hendrix College using a model hybrid rocket using polymethylethracrylate (Plexiglas) as fuel and oxygen gas (O_2) as oxidizer. The spectral measurements were then made on a 50-lb thrust (23 kg) hybrid rocket motor developed in the Dept. Applied Science, University of Arkansas at Little Rock (UALR) by K. Hudson and R. Shanks.[5,6] The principle fuel employed in the hybrid rocket was hydroxyl-terminated polybutadiene (HTPB) with gaseous O_2 as the oxidizer.

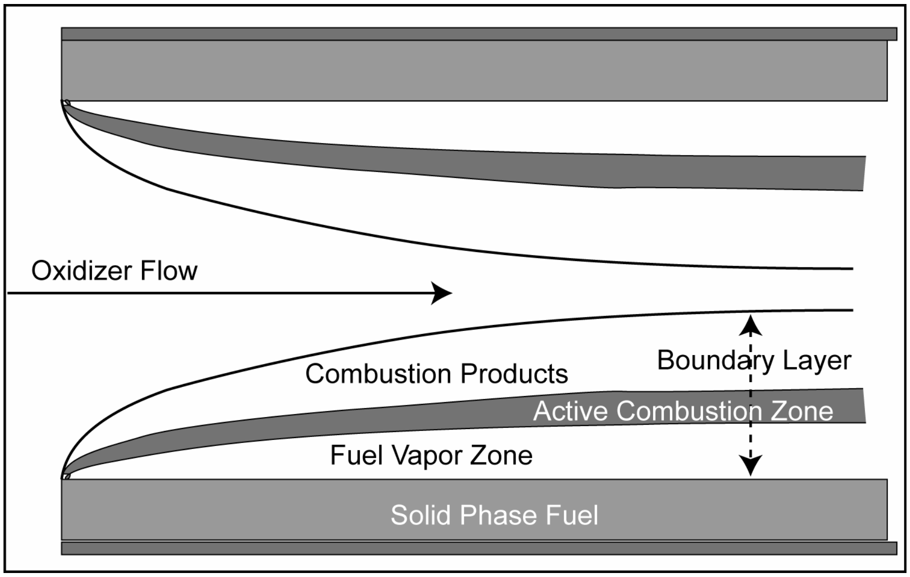

Figure 1. Hybrid rocket combustion model.

Most of the components of the experimental arrangement have been described in earlier reports,[1-4] so only a brief description will be included. The spatial arrangement is shown in Figure 2.

Time-resolved absorption measurements were made by passing a focused light beam from a xenon arc lamp through the hybrid rocket plume. Circular apertures were used to direct the beam and reduce emission interference. The transmitted beam was focused onto the slits of a 0.32-m Model HR-320 JY monochromator equipped with a 2400 groove/mm grating. UV-grade quartz lenses were used to focus the beam. The output of the monochromator was detected with a Princeton Applied Research Corporation Model 1455 intensified charge collection device. A visible filter was placed immediately in front of the monochromator entrance slits when second-order spectra were collected.

The optical bench was tested by detecting the hydroxyl (OH) radical in a "model" hybrid rocket composed of a Plexiglas fuel grain fed with gaseous oxygen. This species has been

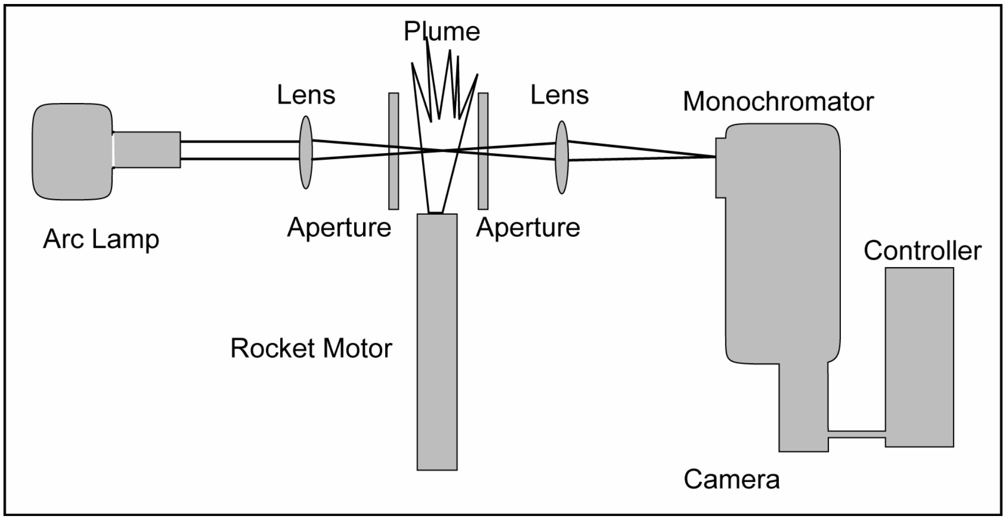

Figure 2. Experimental spectrometer setup.

studied quiet extensively in solid propellant flames and the characterization was relatively straightforward.

In the absorption measurements, the wavelength-resolved intensity of the light source is the primary measurement. This measurement is taken for conditions where the absorber of interest is absent (i.e., the incident intensity, I_0) and where the absorber is present (i.e., the transmitted intensity, I). The absorption is typically represented as the ratio, I/I_0. In this study I_0 is measured prior to combustion of the rocket fuel. During the burn the history of the transmitted beam is recorded by collecting a predetermined number of rapid scans into a number of separate memories. Typically, multiple memories were stored with 25 scans per memory at an exposure time of 20 milliseconds per scan. This provides spectra for 0.50-second time periods for a total of up to 30 seconds detection, more than adequate to provide safety for the personnel and catch the programmed 3-second burns. Background scans with no flame or lamp, and with flame only, are also collected and used to subtract background and flame emission effects, respectively.

Results and Discussion

OH radical absorption spectra were obtained in both first and second order in the 306-nm region of the ultraviolet radiation. Figure 3 is a typical transmittance spectrum from the plume of a Plexiglas model hybrid rocket. This particular one was obtained as a second-order spectrum in the blue flame region approximately 75 mm beyond the rocket body. The absorption includes distinct contributions from the R_1, R_2, and Q_2 bands in the $A^2\Sigma - X^2\Pi$ electronic transition of the OH radical.

Absorption measurements were then made at three different points in the plume of the hybrid rocket motor on three successive firings. The rocket firings were for approximately three seconds: absorption data were collected for 30-second intervals, producing six or seven spectra for each firing. The files were converted to MS-DOS files, edited, and loaded into the program for data analysis.

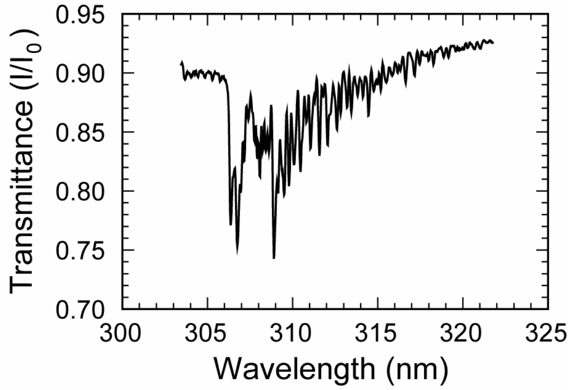

Figure 3. OH radical ultraviolet absorption spectrum.

Absorption path lengths (i.e., plume diameters) were estimated from video records of the rocket firings. The tapes were projected on a large screen and frame-by-frame examinations were performed to obtain the measurements. Rocket diameter and nozzle-to-beam distances were used as reference lengths to determine the video system magnification factor.

The data were analyzed using a multi-parameter curve-fitting routine provided by A. Kotlar .[7] This program utilized 153 rotational transitions over the three vibrational bands, R_1, R_2, and Q_2, in the spectral region of 306 to 312 nm. By comparing known spectral lines, absorption sensitivities, and temperature dependencies to the experimental spectra, a “best fit” is determined, which provides number density and temperature of the OH radical molecules in the flame. Parameters specific to the particular monochromator and detector system were provided to the program for all determinations. Each specific data set was then loaded along with the estimated pathlength for the curve-fitting routine. In most cases, the following parameters were varied to determine the appropriate temperature and number density: number density, temperature, baseline level (background offset), slope, slit width, pixel width, and reference channel.

Figure 4 shows a plot of the experimental and fitted data for one spectrum over the approximately 5-nanometer range covered by the 153 transitions available in the fitting routine.

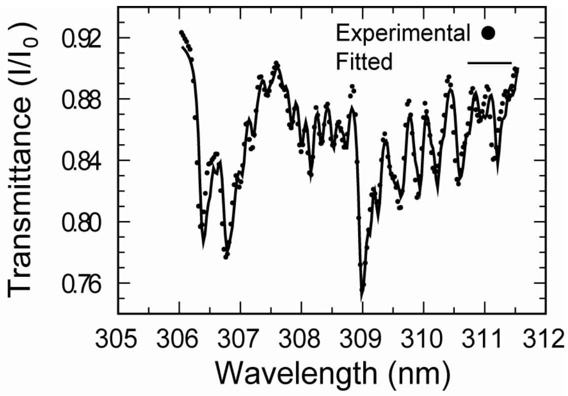

Figure 4. Experimental and fitted spectra.

The pertinent curve-fitted results are compiled in Table 1. The measured plume diameters are listed in column 3. Each value represents an average over the half-second signal accumulation time; in some cases there were significant fluctuations in plume size, but these were usually cyclical in nature and averaged out well. In most cases the plume became irregular toward the end of the burn, so these data are not as reliable as those during the early and middle parts of the firings. The experimental uncertainty is indicated by standard deviation in the table and by error bars on the graphs.

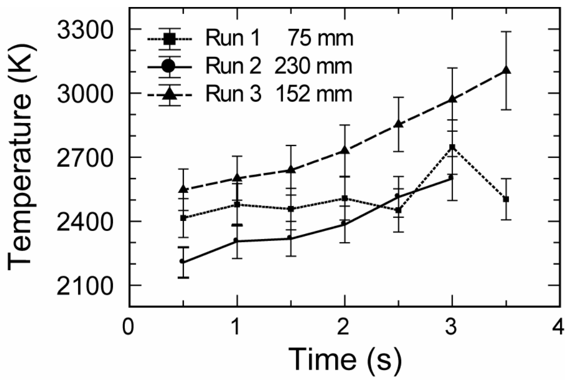

Figure 5. Rocket plume temperature profiles.

Figure 5 represents the results of the measurement of the temperature of the OH radicals in the rocket motor plume at the three different distances. In all cases, the temperature rises during the burn. Since these data were taken on three different burns, no conclusion should be drawn about a spatial temperature profile along the axis of the plume. Figure 6 shows the results of the number density calculations. In all

Table 1. Temperature and OH density values in a hybrid rocket motor plume.

Run	Time (s)	Path Length (cm)	Temp (K)	Std. Dev.	Number Density	Std. Dev.
1	0.50	4.40	2415	91	2.43E+16	1.02E+16
	1.00	5.27	2478	98	2.23E+16	9.30E+14
	1.50	5.73	2457	97	2.08E+16	8.90E+14
	2.00	6.31	2507	101	1.37E+16	8.20E+14
	2.50	6.14	2451	101	2.10E+16	9.30E+14
	3.00	6.48	2747	127	1.78E+16	8.20E+14
	3.50	8.50	2503	96	7.00E+15	3.10E+14
2	0.50	3.50	2207	71	2.15E+16	7.70E+14
	1.00	5.04	2306	80	1.86E+16	7.10E+14
	1.50	5.83	2318	81	1.72E+16	6.50E+14
	2.00	8.82	2385	86	1.22E+16	4.70E+14
	2.50	10.68	2514	95	1.08E+16	4.30E+14
	3.00	10.07	2600	103	1.09E+16	4.80E+14
3	0.50	5.70	2547	97	1.95E+16	8.00E+14
	1.50	8.86	2639	116	1.52E+16	7.30E+14
	2.00	9.55	2730	120	1.42E+16	6.70E+14
	2.50	9.71	2853	127	1.65E+16	8.20E+14
	3.00	10.32	2970	148	1.34E+16	7.10E+14
	3.50	11.41	3105	183	5.50E+15	3.80E+14

cases, the number density decreases during the burn, although these data are not as smooth as the temperature profiles. Again, since the curves represent different burns as well as different distances from the rocket motor nozzle, conjecture about relative values is risky at this point, so no attempt is made to propose a spatial density distribution.

Conclusions

The results of this investigation show that ultraviolet radiation absorption measurements are a convenient, non-intrusive method of measuring temperature and OH radical concentration in a hybrid rocket motor plume. Using the motor at UALR, it was found that the temperature typically varied between 2500 and 3200 K, rising during a firing. Number densities decreased during a typical burn starting at about 2×10^{16} particles/cm^3.

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- Curve fitting: Dr. Tony Kotlar, Army Research Laboratory, Aberdeen Proving Ground, MD.
- Video analysis: Vicki Pillow, The Jennings Snoddy Academic Resource Center, Hendrix College, Conway, AR.

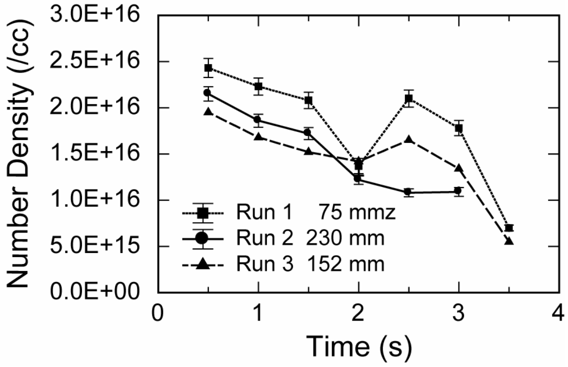

Figure 6. Rocket plume OH radical density profiles.

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