38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit
7-10 July 2002, Indianapolis, Indiana

AIAA 2002-3868

Downloaded by UNIV OF CALIFORNIA SAN DIEGO on October 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/6.2002-3868

UV SPECTROSCOPIC MONITORING OF ROCKET MOTOR COMBUSTION EFFICIENCY

M.W. Teague, Professor of Chemistry, Member AIAA
T.A. Jennings, Undergraduate Student
A.M. Wright, Assistant Professor of Physics, Member AIAA
Hendrix College
1600 Washington Avenue
Conway, AR 72032

A.B. Wright, Professor of Applied Science and Systems Engineering, Member AIAA
University of Arkansas at Little Rock
2801 S. University Avenue
Little Rock, AR 72204

Abstract

Ultraviolet absorption spectroscopy was used as a non-intrusive probe to measure OH radical temperature in the plume of a 2.5-in. hybrid rocket motor. Continuous radiation from a xenon arc lamp was passed through the rocket plume onto the entrance slits of a monochromator equipped with an intensified charge-coupled device array detector and absorption was measured around 306 nm. The data are analyzed using a multi-parameter curve-fitting routine. This program utilizes 153 rotational transitions over the three vibrations band, R_1, R_2, and Q_2, in these spectral regions (306-312 nm). The program determines number density (concentration) and temperature of the OH radical. The OH concentration was measured in the hybrid rocket motor plume over a range of oxidizer flow values. The results show that the OH concentration does increase with flow rate at low flow, level off at intermediate flow, and drop at higher values

Introduction

Earlier this group reported the use of ultraviolet absorption as a tool for understanding the chemistry of solid fuel burning for the purpose of improvement of currently-used fuels and the development of new materials [1,2]. Because the burning is rapid, complex, and variable, investigative methods must be fast and non-intrusive. This work uses an adaptation of techniques developed by Vanderhoff, et. al.[3-6] in which absorption of ultraviolet and visible light was used to detect and measure species involved in solid propellant combustion at modest pressure.

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 those 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.

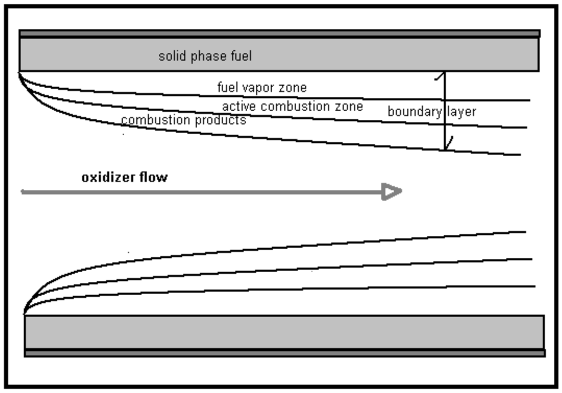

Figure 1. Hybrid rocket combustion

In the boundary layer between the fuel and oxidizer flow, combustion takes place in 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

Spectral measurements were made on the 2.5-in, 50-lb thrust hybrid rocket motor in the Department of Applied Science at the University of Arkansas at Little Rock (UALR). It was developed and assembled and is operated under the direction of Dr. Keith Hudson.[7] The principle fuel employed in the rocket

Copyright © 2002 by the author(s). Published by the American Institute of Aeronautics and Astronautics, Inc., with permission.

Downloaded by UNIV OF CALIFORNIA SAN DIEGO on October 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/6.2002-3868

motor is hydroxyl-terminated polybutadiene (HTPB) and gaseous O_2 used as the oxidizer.

The present work is a new approach to engine efficiency based on calculations by Cohen, et al, presented at the 35th Joint Propulsion Conference and Exhibit in June 1999.[8] Their use of a one-dimensional kinetics code indicated that OH molecule concentration at the exit of a Titan IV engine should be a sensitive marker of mixture ratio. The mole fraction of OH is expected to reach a maximum at the stoichiometric point for fuel/oxidizer ratio. The spectra acquisitions for this project were made over a period of time as "piggy-back" experiments at the University of Arkansas at Little Rock (UALR) during firings made by Dr. Ann Wright.

Most of the components of the experimental arrangement have been described in earlier reports, so only a brief description will be included. The spatial arrangement is shown in figure 2.

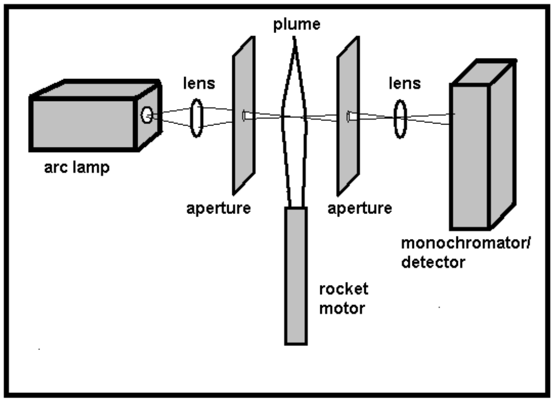

Figure 2. Experimental schematic

Time-resolved absorption measurements were made by passing a focused light beam from a xenon arc lamp through the hybrid rocket plume. Small circular apertures were used to direct the beam and reduce emission interference. The transmitted beam was focused onto the slits of a SpectraPro 300i 0.300-meter monochromator (Acton Research Corporation) equipped with a 2400 groove/mm grating, usually tuned to the second order diffraction range. The output of the monochromator was detected with a Princeton Instruments ICCD-MAX intensified 2-D CCD camera.

The optical bench was tested by detecting the OH radical in a "model" hybrid rocket composed of a Plexiglas fuel grain fed with gaseous oxygen. This specie has been studied quite 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_o) and where the absorber is present (i.e., the transmitted intensity, I). The transmittance is typically represented as the ratio, I/I_o. In this study I_o 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 10 scans per memory at an exposure time of 30 ms per scan. This provided spectra 0.30-s time periods for a total of up to 20 seconds detection, more than adequate to provide safety for the personnel and record the programmed 3-second burns.

In some cases, 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 examination was performed to obtain the values. Rocket diameter and nozzle-to-beam distances were used as reference values to determine the video system magnification factor.

In this study, spectra were obtained using hydroxyl-terminated polybutadiene (HTPB) fuel. N-100 was the cross-linking compound in all cases. The data were analyzed using a multi-parameter curve-fitting routine provided by Dr. Anthony Kotlar of the Army Research Laboratory (ARL), Aberdeen Proving Ground (APG), Maryland.[9] This program utilizes 153 rotational transitions over the three vibration bands, R_1, R_2, and Q_2, in this spectral region (306-312 nm). 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 estimated pathlength when available. 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.

Results and Discussion

OH absorption spectra were obtained in both first and second order in the 306-312 nm region of the ultraviolet spectrum. Figure 3 (appended) 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 150 mm beyond the rocket body. The absorption includes distinct contributions from the R_1, R_2, and Q_2 bands in the $A^2E\text{-}X^2\prod$ electronic transition of OH.

Spectra were taken during several rocket motor firings, and an attempt has been made to choose

Downloaded by UNIV OF CALIFORNIA SAN DIEGO on October 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/6.2002-3868

those runs in which operating parameters such as fuel flow rate, nozzle characteristics, and pressure were as consistent as feasible. A typical spectrum is shown in Figure 4 (appended) showing the experimental data points as the dotted line. The curve-fitted results are shown in the solid spectrum. Figure 5 (appended) shows the results of the OH number density determinations vs. the gaseous oxygen flow rates. The data points in the graph are averages of at least three runs at the indicated flow rates, within the control parameters of the experimental setup.

Conclusions

Our results show that the OH concentration in the plume of a hybrid rocket motor does increase with flow rate at low flow, level off at intermediate flow, and drop somewhat at higher values. The maximum value was around 0.10 lb/min flow rate. We are now calculating the regression rate of the fuel to determine the values of the fuel and oxidizer flux. From this we will determine the mixture ratio corresponding to oxidizer flow value, allowing us to compare our measured maximum with the calculated stoichiometric oxidizer/flow point for the rocket motor.

References

1. M. W. Teague, T. Felix, J. K. Hudson, R. Shanks, “Application of UV-VIS Absorption to Rocket Plumes,” AIAA 95-2790, 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 1995.

2. M.W. Teague, J. R. Welborn, T. M. Felix, M. K. Hudson, and J. Willis, “UV/Vis Absorption as a Diagnostic for NO in Rocket Plumes,” International Journal of Turbines and Jet Engines, February, 1997.

3. J. A. Vanderhoff, “Spectral Studies of Propellant Combustion: Experimental Details and Emission Results for M-30 Propellant,” BRL-MR-3714, Aberdeen Proving Ground, MD, December 1988.

4. J. A. Vanderhoff, “Spectral Studies of Propellant Combustion: II. Emission and Absorption Results for M-30 and HMX1 Propellants,” BRL-TR-3055, Aberdeen Proving Ground, MD, December 1989.

5. M. Warfield Teague and J. A. Vanderhoff, “Spectral Studies of Propellant Combustion: III. Emission and Absorption Results for HMX2 Propellant,” BRL-MR-3911, Aberdeen Proving Ground, MD, May 1991.

6. John A. Vanderhoff, M. Warfield Teague, and Anthony J. Kotlar, “Absorption Spectroscopy Though the Dark Zone of Solid Propellant Flames,” BRL-TR-3334, Aberdeen Proving Ground, MD, April 1992.

7. Robert B. Shanks, “A Labscale Rocket Motor and Facility for Plume Diagnostics and Combustion Studies,” Ph. D. dissertation, Department of Applied Science, University of Arkansas at Little Rock, Little Rock, AR, 1994.

8. L.M. Cohen, K.M. Jassowski and J.I. Ito, “Mixture Ratio Distribution in a Titan IV Rocket Engine Using Laser-Induced Fluorescence of OH,” 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Los Angeles, CA, AIAA 99-2169, June 1999.

9. John A. Vanderhoff and Anthony J. Kotlar, “Improving Spectral Fits of Absorption Data Taken with an Array Detector: Wavelength ‘Linerization’,” BRL-MR-3866, Aberdeen Proving Ground, MD, September 1990.

Acknowledgements

We would like to thank the following for assistance on this project:
Facilities: Department of Applied Science and Systems Engineering, University of Arkansas at Little Rock.
Financial: Stennis Space Center, Arkansas Space Grant Consortium, and NASA EPSCoR.

Downloaded by UNIV OF CALIFORNIA SAN DIEGO on October 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/6.2002-3868

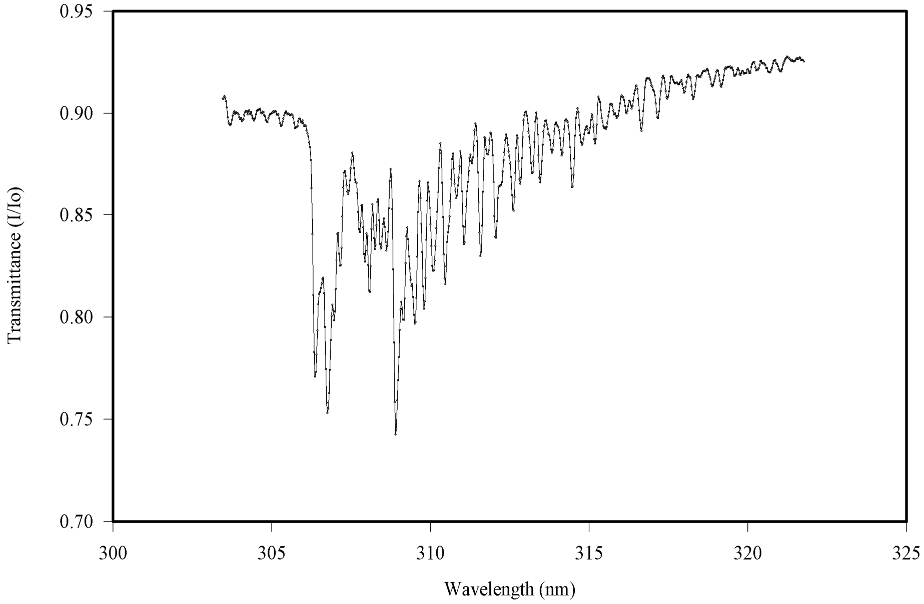

Figure 3. OH Absorption in a model hybrid rocket plume

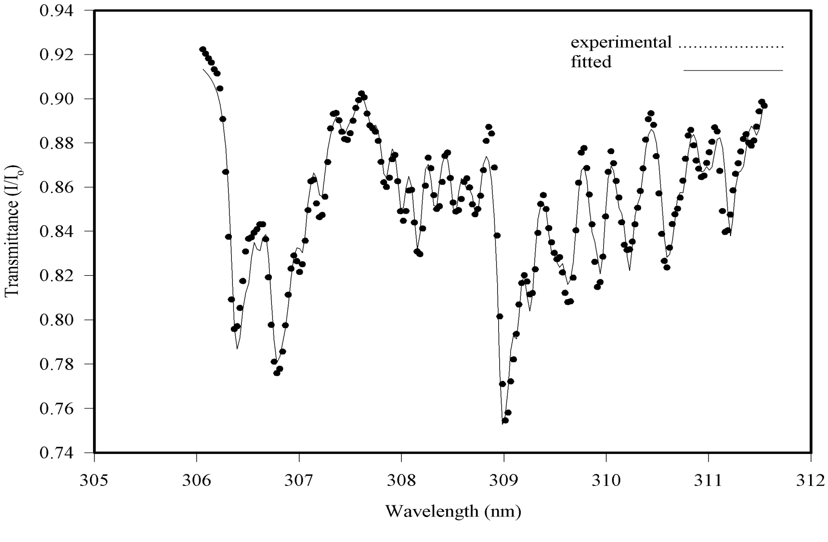

Figure 4. Experimental and fitted spectra

Downloaded by UNIV OF CALIFORNIA SAN DIEGO on October 15, 2015 | http://arc.aiaa.org | DOI: 10.2514/6.2002-3868

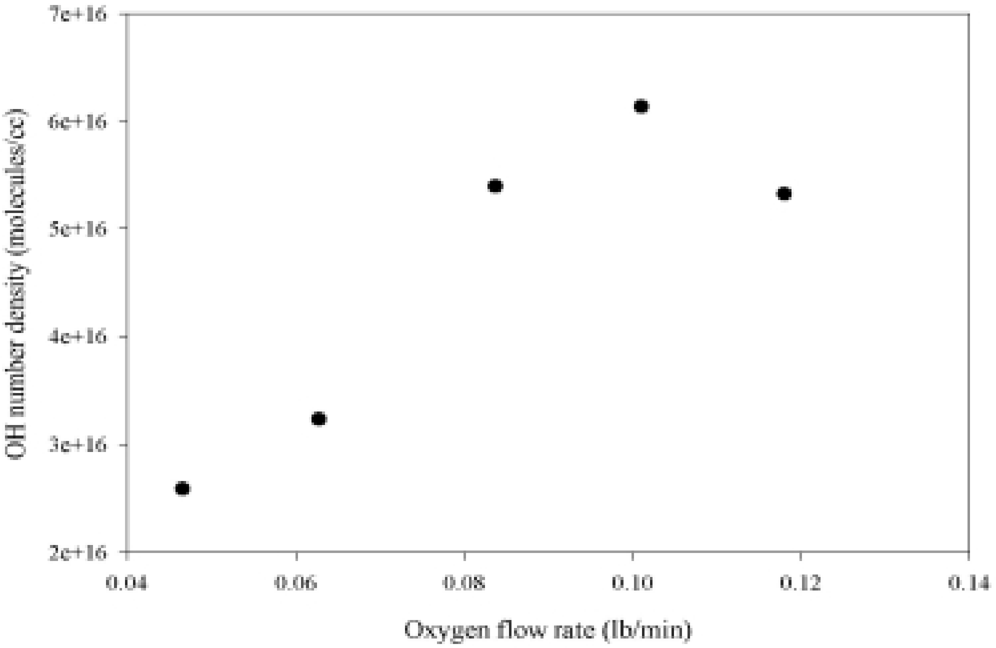

Figure 5. OH concentration as a function of oxidizer flow.