Optical Studies of Combustion Chamber Flame in a Hybrid Rocket Motor

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ABSTRACT

The oxygen injector head in UALR's labscale hybrid rocket motor has been redesigned to include a coaxially located optical port. This port permits viewing directly into the space in front of the fuel grain where combustion is initiated. It is designed to allow a visible-imaging fiber optic, a UV-Vis fiber optic, or an infrared fiber optic to be aligned coaxially with the motor. The imaging fiber optic shows swirling and pulsating flow fields, which indicate that one-dimensional flow model assumptions are not valid. The quartz fiber optic is used with a UV-Vis spectrometer to perform spectral studies using fuels doped with metals. It is demonstrated that the same species that are seen in the plume can be detected in the combustion zone, which permits comparison of species at the two end points of the combustion process.

Keywords: hybrid rocket motor, spectroscopy, flow patterns, metal emission spectra, combustion diagnostics

Introduction

A chemical hybrid rocket motor contains a solid, stationary fuel element and a fluid oxidant that is pumped into contact with the fuel. This is distinct from a liquid rocket motor where both the fuel (hydrogen) and the oxidant (oxygen) are mixed or a solid rocket motor where the fuel and oxidant are combined in the propellant grain.

In 1993, a labscale hybrid rocket motor facility, complete with computer control and data acquisition system, was designed and constructed at the University of Arkansas at Little Rock (UALR) (see Figure 1). This facility has aided the aerospace community in numerous studies on hybrid rocket motors including their possible future use

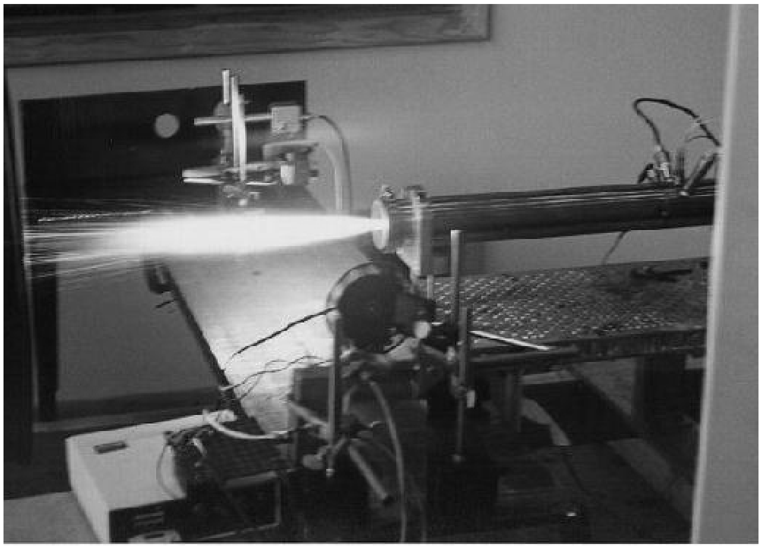


Figure 1. UALR hybrid rocket firing.

as boosters on the Space Shuttle Main Engine (SSME).[1] While these studies are of general interest, some may not be well known to the readers of this journal. For that reason, much of the introduction to this paper is devoted to briefly recounting those studies and providing literature references to them.

UALR's hybrid rocket motor uses hydroxyl-terminated polybutadiene (HTPB) as its fuel and gaseous oxygen as the oxidant. The rocket motor is operated in a controlled, variable oxygen-to-fuel ratio range of 1.5 to 4.5, by varying the oxygen mass flow in a range of 0.018 to 0.037 kg/s. At an oxygen-to-fuel ratio of 2.074, HTPB burns stoichiometrically to carbon monoxide (CO) and water vapor (H_2O). The temperature in the combustion chamber is above 3000 °C, providing sufficient energy for the atomization process.

Several studies were conducted using different spectral techniques. Spectral emission in the hybrid rocket plume was detected in the ultraviolet-visible (300–750 nm), near infrared (near IR) (750–800 nm), and mid-infrared (2–16 μm) regions,[2] and a baseline emission curve from 250 to 800 nm was produced.[3] The fuel was doped with metallic salts of varying concentration, and atomic line and molecular band emissions were measured, and intensity versus concentration curves for manganese, magnesium, and strontium were determined. Infrared studies were conducted with a Fourier-transform infrared (FTIR) spectrometer,[4] and work is underway to extend the infrared measurements to 1100 nm.

Absorption spectroscopy techniques were applied to determine nitrous oxide (NO) concentration and hydroxide (OH) concentration in the plume.[5,6] The OH concentration gives a measure of combustion efficiency and may be used in a feedback scheme to modulate the oxygen flow and to optimize the combustion efficiency during regression of the fuel. Although OH concentration has been measured only in the plume, pre-combustion chamber measurements might provide better control response.

Studies to characterize the physical parameters of the hybrid rocket such as pressure, plume flicker, acoustical output, and thrust have been performed at the UALR facility.[7,8] Additionally, pressure transducers have been placed in both the pre-combustion and the post-combustion chambers. The following studies have been completed: 1) correlation between the two pressure transducer signals; 2) preliminary analysis to determine chaos in the pressure signals, and 3) correlation between flicker in the plume and variations in the pressure signal. The frequency of oscillation is identical for the two pressure transducers and the plume flicker.

A novel ion detector was used to detect charged species in the plume.[9] This detector measures the current induced when the particles pass through a conducting cylinder. The induced current measurement can be used to determine what metallic species are present in the plume, and the ion detector signals have been correlated to the pressure signals. This has shown that downstream from the nozzle, the metallic ions dominate the response over the charge associated with combustion products, making the ion detector an excellent candidate for engine health monitoring.

In conjunction with the diagnostic measurements, the effects of energetic additives on thrust have been studied.[10] Guanidinium azo-tetrazolate (GAT) and amino-guanidinium azo-tetrazolate (AGAT) were added to the HTPB fuel mixture, and both additives increased the regression rate of the fuel.

NASA's John C. Stennis Space Center (SSC), a leader in exhaust plume diagnostics, uses plume spectroscopy for vehicle health management (VHM).[11] Diagnostics for VHM are provided by atomic spectral emission techniques. The measurement of excited atomic species in the motor plume can be correlated to the amounts of metallic species introduced by failures in engine components leading to predictions of possible failures. Most of these studies, however, have been conducted on liquid rocket motors. Should the space community adopt the hybrid rocket motor, which has a much more complicated plume, fundamental work must be performed to adapt these spectroscopic techniques.

Although UALR, SSC, and other rocket facilities have conducted extensive research on the external parameters of the hybrid rocket plume, no studies have been conducted viewing, characterizing, or collecting data from the pre-combustion chamber during firings (see Figure 2). Studies of the initial combustion zone would augment previous plume studies and offer informa-

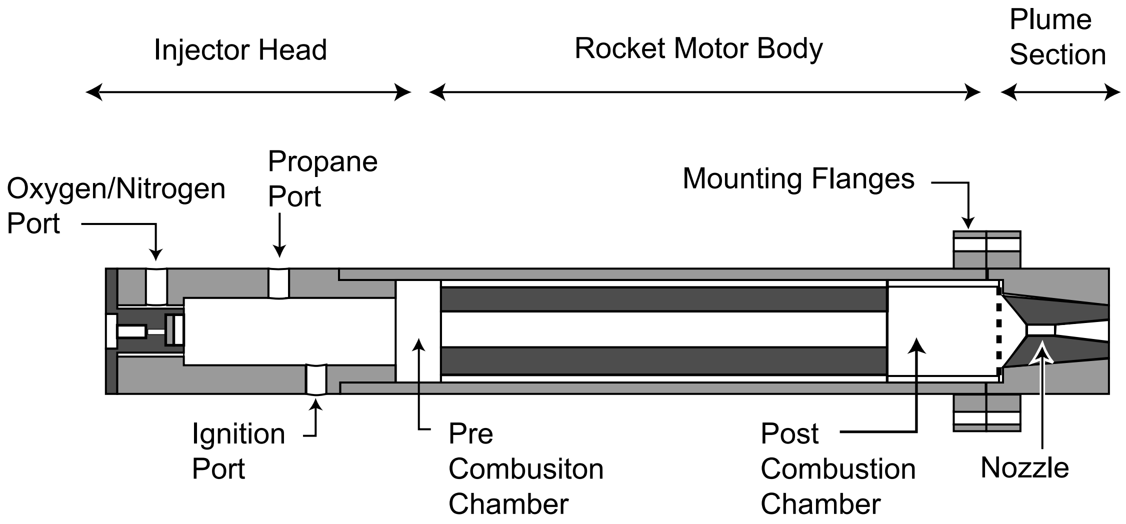


Figure 2. Schematic of UALR's labscale hybrid rocket motor.

tion for comparative analysis. Viewing the inside of the motor will provide oxygen-to-fuel ratio data and internal flow characteristics of a healthy engine.

Design

Injector Head

The oxygen injector head in UALR's labscale hybrid rocket motor is designed to include an optical port (see Figure 3).This port is located coaxially with the center-line of the rocket motor and allows direct viewing into the pre-combustion chamber (see Figure 2). A visual imaging fiber optic is used to transmit the image of the burning fuel grain to a charge-coupled device (CCD) camera. Alternately, an ultraviolet fiber optic is used to collect UV-Vis spectral data and transfer it to a spectrograph. Plans exist to observe the near IR region; however, difficulties with flicker make this measurement much more challenging than the other two measurements. Additional research and instrumentation will be required.[4]

The injector head design consists of two sections: the injector head shaft (IHS) and the fiber optic plug (FOP). The gas inlet ports are located on the side of the IHS so that the FOP could be axially located (see Figure 3).

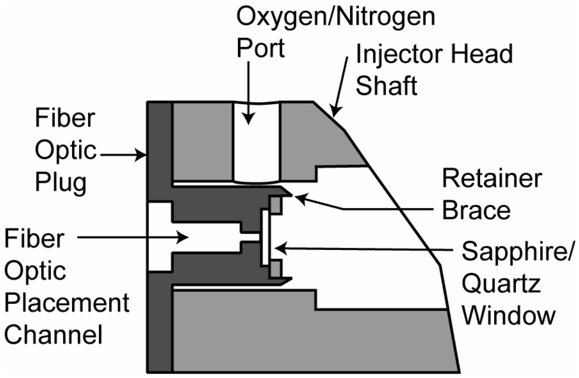


Figure 3. Cross section of injector head shaft (IHS) and fiber optic plug (FOP).

Protecting the fiber optics from the combustion chamber temperature and pressure was a primary design concern. A 2-mm thick quartz (for imaging or UV-Vis) or sapphire (for near IR) window separates the fiber optic from the combustion chamber pressures, temperatures, and reactive species. The FOP was designed to be easily removed, while maintaining the challenging sealing requirements. This design allows windows to be switched or cleaned without disassembling the rocket motor. O-rings are used to seal the FOP and the window, so that hot combustion gases cannot escape through the head of the motor.

Optical Systems

Two different optical setups have been used to date: imaging (borescope) and UV-Vis. The imaging optical system includes an imaging fiber optic (borescope), coupling devices, neutral density (ND) filters, a CCD camera, a video cassette recorder (VCR), and a television monitor (see Figure 4). A Hawkeye 17 focusing borescope is used to collect visual images. The borescope eyepiece is inserted into a ND filter holder that mounts to a bracket that supports the borescope and maintains the distance between the borescope eyepiece and the FOP window. Kodak Wratten gelatin film is used as the ND filter, which provides flat attenuation of light intensity across the visible spectrum. The CCD camera lens fits into the other side of the ND filter holder. A black and white CCD camera with NTSC output transmits the image to a VCR or TV. The images were not inverted by the borescope or the camera lens.

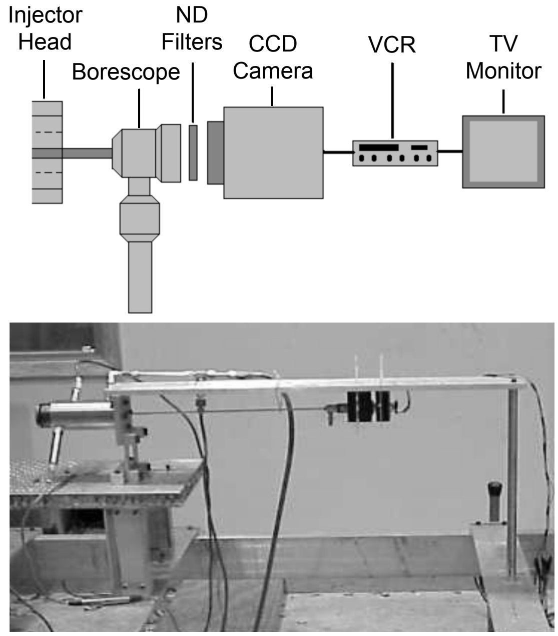


Figure 4. Schematic and picture of imaging system.

The UV-Vis system (see Figure 5) uses a quartz window in the FOP. For maximum transmittance efficiency, a 1-m long quartz fiber optic with 10:1 core/clad ratio is inserted into the FOP and connects to a SPEX270M spectrograph. The quartz fiber passes 300 to 750 nm light without distortion. The SPEX270M uses a grating to spread the incident light onto a 1024 pixel silicon photodiode array (PDA). A wavelength selector allows the wavelength at the center of the PDA to be set. The output of the spectrograph is interfaced to and controlled by a portable PC computer. The spectrograph system (for plume spectroscopy) has been described previously.[12]

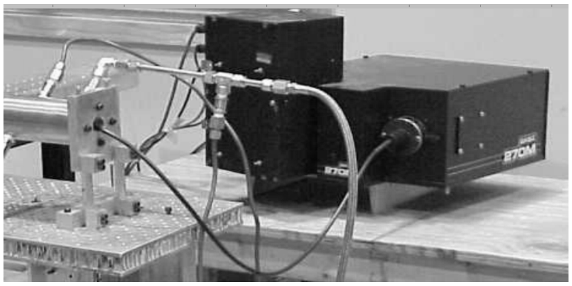


Figure 5. Picture of UV-Vis spectroscopic system.

Experimental

Imaging

Initially, eight experiments were performed, two each at chamber pressures of 1379 kPa (200 psi), 1724 kPa (250 psi), 2413 kPa (350 psi), and 3103 kPa (450 psi). The fuel used was HTPB cured using Desmodur N-100 (1,6-hexamethylene diisocyanate, Bayer) with 1% carbon added as an opacifier. The carbon provided particles that enhanced the visual images. Each firing lasted three seconds. Multiple firings were performed with the same fuel grain until the fuel was expended. Movies of representative firings are available for download.[13–15]

Steady state flow patterns occurred in less than one second after combustion began. The flow pattern in every firing indicated two effects: a clockwise rotational pattern about the axis of the motor and a pulsating pattern along the axis of the motor. The flow field was clearly three-dimensional and turbulent. At the end of each firing, the light at the center of the motor diminished and then intensified. This corresponded to the shutoff of the oxygen where the combustion became fuel rich.

The clockwise rotational pattern explains some observations of the fired fuel grains. The bore of spent fuel grains is generally smooth and circular. A one-dimensional flow along the bore would not generate these features, since variations in the fuel mixture would create lean and rich pockets at different points in the fuel, resulting in an uneven, pitted surface. However, the rotational flow field carries oxygen around the circumference of the grain such that more complete mixing occurs.

Many researchers have postulated a parabolic flow boundary layer along the grain.[4,16] This effect would appear much like water flowing down a drain, and it can be clearly seen in the current visual images.

There are two theories about how hybrid fuel grains burn. One theory presumes a double layer combustion in which the fuel melts and then vaporizes into a fuel/oxidant combination.[4] The other theory presumes that the fuel sublimes into a fuel/oxidant mixture.[16] Identifying the correct mechanism is important since the melting phenomena introduces combustion mechanistic steps and associated kinetic parameters (like rate constants) that may be very important as the model is scaled. Even though the melt layer may be small, it must be proven to be insignificant before it can be neglected. The rate constants associated with the melt layer may give rise to some of the combustion oscillations seen with hybrid rocket motors.

In a separate work,[17] it was discovered that liquid droplets of HTPB were present in UALR's hybrid rocket plume. In the current work, it appears in the visible images that a melt layer exists around the edge of the burning zone. Liquid droplets could not exist in the plume without a melt layer, and the visible images support this conclusion.

Including swirl in a theoretical model dramatically increases computational load.[18] It should be neglected unless the effect can be shown to be significant. However, failure to include the effects, if they exist, will result in underestimation of the key modeling features, such as thrust, specific impulse, and efficiency. The video images show definitively that this effect cannot be neglected in hybrid rocket motors.

Why the rotation was clockwise in all firings has not been explained. In a perfectly symmetric motor, there should be no predisposition for rotation to start in a particular direction, and it would be expected that the rotation would sometimes be clockwise and other times counterclockwise. The best explanation to date is that minor asymmetries in this particular rocket motor make clockwise the preferred rotational direction. For instance, the oxygen inlet may not be perfectly aligned with the motor center line.

The visual images show pulsations into the pre-combustion chamber. This can be seen by a brightening of the background light and by particulate matter moving toward the camera. The pulsating flow pattern is consistent with an expected longitudinal acoustic mode associated with a cylinder. The pressure measurements in both the pre-combustion chamber and the post-combustion chamber show evidence of acoustic modes among other oscillations.[7,8]

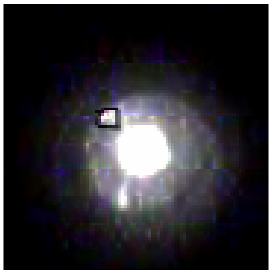
Since acoustic modes sometimes couple with the combustion process and give rise to chaotic behavior, chaos may exist in the hybrid rocket motor process. Preliminary investigation was made to detect chaos in the pressure signals, and, for the higher flows, it appeared to be present. The presence of chaotic oscillations and the oxygen mass flow where transition to chaotic behavior occurs needs to be investigated further since it will impact both the modeling and the design effort.

Although oxygen is being directed into the pre-combustion chamber at pressure, waves are free to propagate along the cylinder of the motor between the impedance set by the nozzle and chamber at the post-combustion end and the chamber at the pre-combustion end (see Figure 2). The visual evidence of a pulsating flow in the injector head further supports longitudinal acoustic modes as the basis for some of the pressure oscillations in hybrid rocket motors.

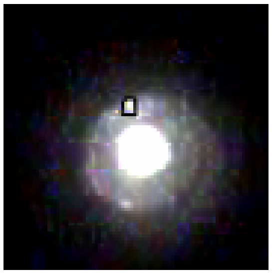
The swirling pattern was more clearly defined for fuel grains that had been fired one or more times than for fuel grains that were being fired for the first time. This could be due to the char layer deposited from previous firings acting as an opacifier. The soot particles may add to the visualization of the swirling effect. Further, with a larger center bore, the swirling pattern is larger.

In one of the 450 psi chamber pressure firings a large, clearly visible particle provided clear evidence of the rotational flow pattern (see Figure 6). Although it is obvious in the moving images, the particle in the still images has been outlined to enhance its visibility. The particle is first seen (upper most frame in Figure 6) at 11:00 (upper left quadrant) in the image near the periphery. One frame later (at the 30 Hz NTSC sample rate), the particle has moved to approximately the 12:00 position (middle frame in Figure 6). One frame later, it has moved to 1:00 (bottom most frame in Figure 6). This gives an approximate rotation rate of 24 radians per second for this flow condition.

Particle at 11:00



Particle at 12:00



Particle at 1:00

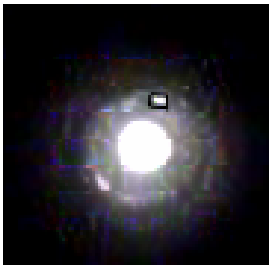


Figure 6. Sequential images looking down bore of hybrid rocket with rotating particle outlined.

UV-Vis

The initial study performed with the UV-Vis spectrograph was to gather baseline information for the combustion chamber area. The entrance slit width was set to 22 µm, the same as that used with previous plume emission studies at UALR.

The rocket motor was fired for three seconds twice at 1379 kPa (200 psi) and twice at 1724 kPa (250 psi). The wavelength selector on the spectrograph was set for different portions of the spectrum in the separate experiments (500–650 and 620–770 nm). The control computer initiated the spectrograph two seconds prior to firing and stopped the spectrograph after shutdown. The spectrograph collected the emission in the UV-Vis range 100 times every 0.1 seconds for each experiment.

A “waterfall” plot for each wavelength selector position is plotted (see Figures 7 and 8). The *z*-axis on this plot is the analog-to-digital converter (ADC) value from the spectrograph’s CCD camera as read by the computer card. The *x*-axis is the time throughout the firing. For clarity, the *x*-axis was down-sampled to provide a plot every 500 milliseconds. The *y*-axis is the wavelength from the spectrograph. The initial ignition event and the shutdown event can be seen. At shutdown, emissions approach the blackbody configuration due to soot and smoke that are formed in the fuel rich condition. This can be observed as well in the videos of the combustion chamber. During the middle portion of the firing, the emissions stabilize to a steady state condition for about one second. In Figure 7, the sodium resonance line continuum can be seen centered at 590 nm. In Figure 8, the potassium line/ continuum can be seen at 740 nm.

(There is a section of several pixels in the center of the CCD camera that consistently reads low. This results in an inverse peak in the center of each graph and does not represent a spectral feature.)

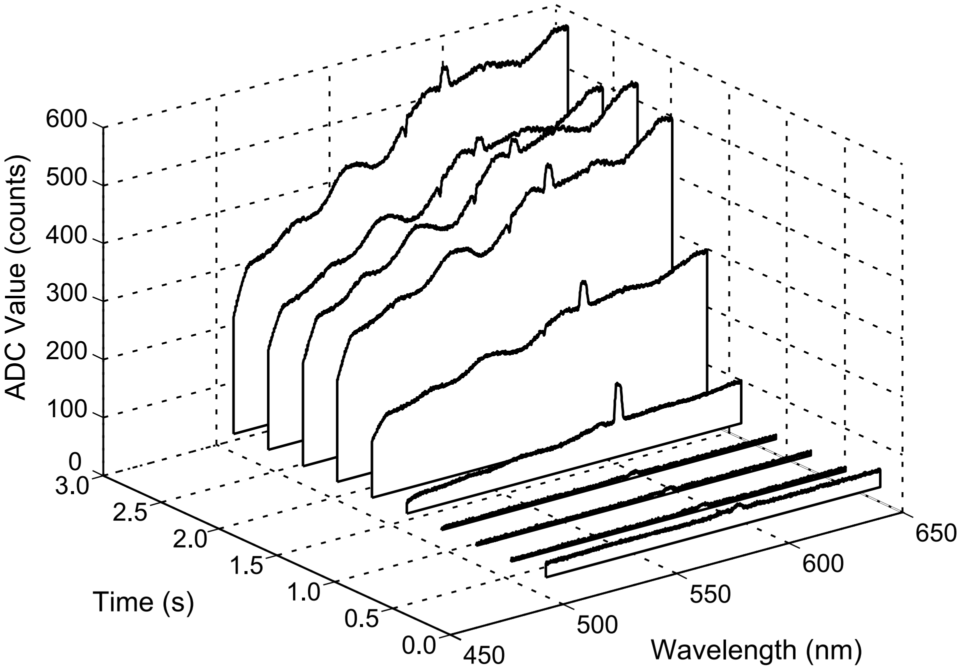


Figure 7. Waterfall plot for a hybrid rocket motor firing (sodium).

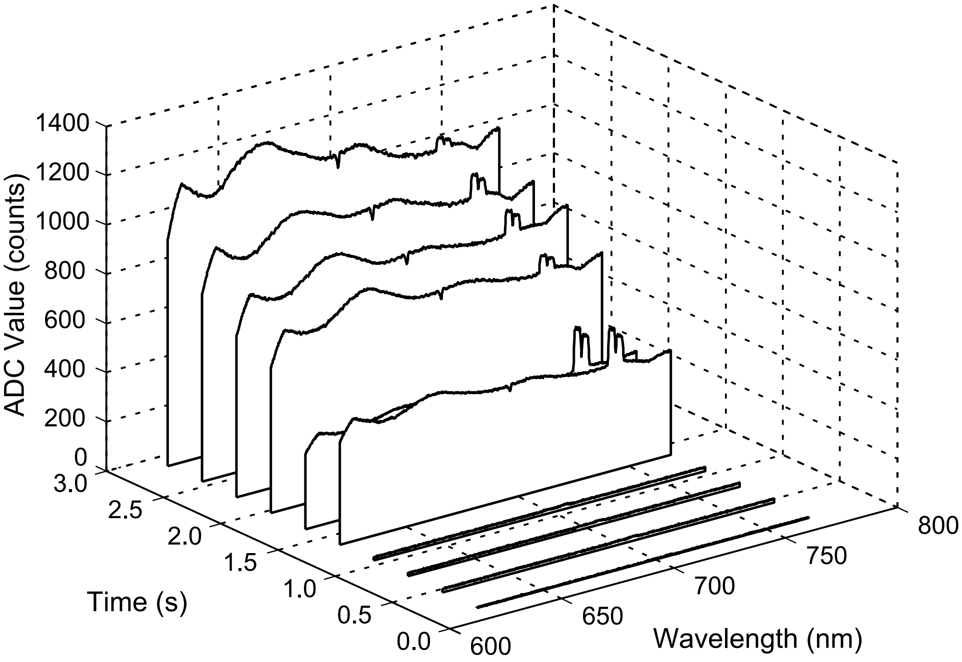


Figure 8. Waterfall plot for a hybrid rocket motor firing (potassium).

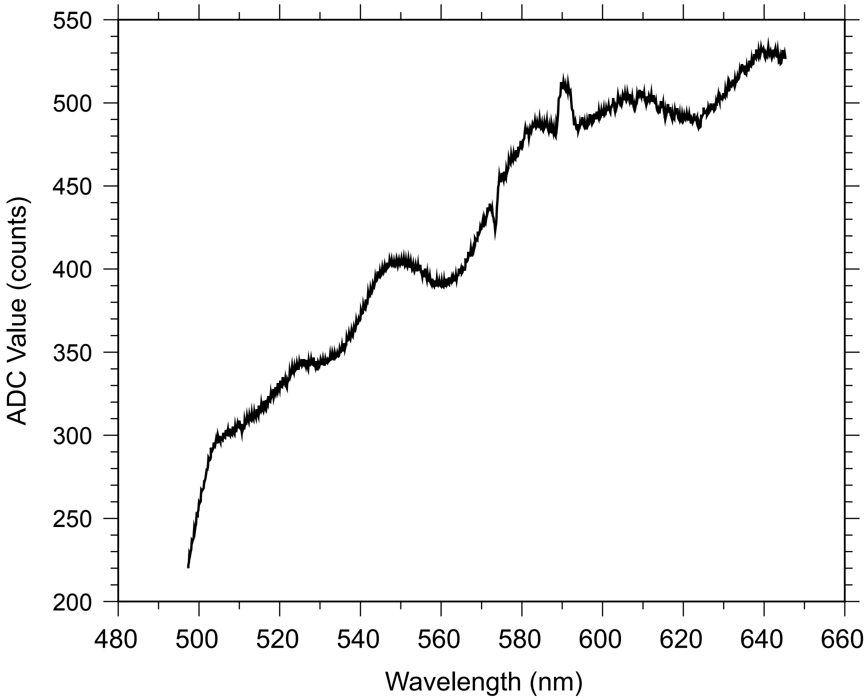


Figure 9. Averaged UV-Vis spectrum inside combustion chamber (sodium).

Several spectra were averaged for the steady-state emissions (between initiation of combustion and the blackbody shutdown spectrum). In Figure 9, the sodium resonance line/continuum can be seen centered at 590 nm. In Figure 10, the potassium line/continuum system can be seen centered at 740 nm. These spectra can be compared with plume spectra from previous studies using the labscale hybrid rocket motor for similarities.[3] Increased emissions are observed. These may be due to increased blackbody emissions, especially considering that the injector head view is directed to the graphite nozzle at the rear of the chamber. The spectra generated from in-plume measurements represent completed combustion; however, chamber combustion should have char and other materials coming off the fuel grain surface, which give rise to increased black body emissions. Molecular bands are present that appear to be similar to those in previous plume studies.[12] Further experiments are planned to fully characterize the baseline emissions in the combustion chamber. However, the current experiments validate the ability to extract useful information from the injector head mounted optics.

Conclusion

The swirling, pulsating flow observed in the combustion chamber indicates that the one-dimensional flow assumptions are not valid. This study provided visual information that characterizes the internal combustion chamber flow as three-dimensional.

The in-chamber UV-Vis measurements performed in this study are correlated with previous in-plume UV-Vis studies. This measurement in conjunction with plume measurements can be used to characterize the effects of combustion as it progresses through the rocket motor and the effects of afterburning.

The blackbody component in the chamber is higher than in the plume, probably due to the graphite nozzle at the end of the chamber. The nozzle forms a very good approximation of a blackbody source during firing due to its material, surface, and shape. At the end of the firing, the blackbody radiation due to soot swamps the rest of the spectrum. This is also seen in the visual images as the emission extinguishes at the end of the firing.

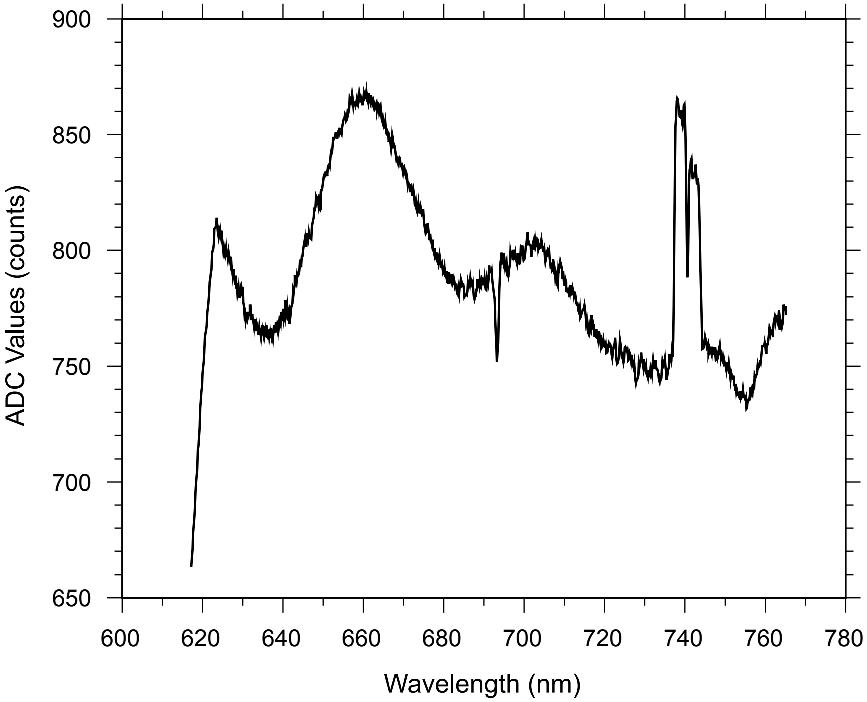


Figure 10. Averaged UV-Vis spectrum inside combustion chamber (potassium).

Acknowledgement

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