Multi-Wavelength Laser Opacity Study of a Hybrid Rocket Plume

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ABSTRACT

An instrumentation system was developed to measure the opacity of a hybrid rocket plume as a function of optical wavelength. The source consisted of collineated beams from two lasers, providing seven wavelengths in a single probe beam. Detection was accomplished with a spectrograph equipped with a photodiode array.

Previous work with a two-wavelength system demonstrated the ability to follow the changes in opacity level of a hybrid rocket plume during the various stages of a typical firing cycle. The present work was to investigate the feasibility of using a multiple wavelength system to acquire more detailed information about the particulates present in the hybrid rocket plume.

Qualitative analysis of the plume particulates was done by comparison of the relative extinction coefficients of the laser wavelengths with published extinction coefficient curves from Mie scattering theory. While it was found that light level fluctuations in the system prevent definitive conclusions, the data suggests that the particulate matter in the plume may consist of some optically transparent material. This is in contrast to the absorbing, soot-like material that might be expected in a hybrid rocket plume.

Keywords: combustion diagnostics, rocket ground testing, particle analysis, opacity, aerosol, hybrid rocket

Conversion Chart [English to Metric]

1 lbm = 1 pound mass = 454 g
1 psi = 1 pound per square inch = 0.145 kPa

Introduction

It is desirable to know the characteristics of the particulates present in the plume of a hybrid rocket motor. This information could prove useful in the investigation of combustion instabilities in hybrid motors, and it is important in interpreting other optical plume studies being conducted at the University of Arkansas at Little Rock, Hybrid Rocket Facility (UALR HRF). To this end, a system is being developed to measure the plume particulate characteristics via opacity measurements fit to Mie scattering theory.

For many, Mie scattering theory (developed by G. Mie in 1908) may not be familiar. Mie scattering is characteristic of spherical particles, such as aerosol droplets, for which all wavelengths of incident light are scattered equally. This is in contrast to the more-familiar Rayleigh scattering, the selective scattering of shorter wavelengths by particles that are non-spherical, such as carbon char and soot. Mie scattering is described by a series of infinite terms and, given enough computer time, it can provide a rigorous solution for spherical particles. However, rapid approximations can be used for particles larger than about 5 μm and smaller than about 0.1 μm.[1,2]

Also, “absorbing” and “non-absorbing” particles will be discussed. Absorbing particles are those such as carbon char or soot, which scatter and absorb part of the incident light. An aerosol droplet of India ink would also be an absorbing particle. Non-absorbing particles are transparent, such as aerosolized water droplets, which transmit most of the incident light.

Previous work done at UALR[3] led to the development of a dual wavelength, laser based, opacity measurement system. That work investigated the feasibility of using a laser-based system for plume opacity measurements. The dual wavelength system, consisting of the 633 nm

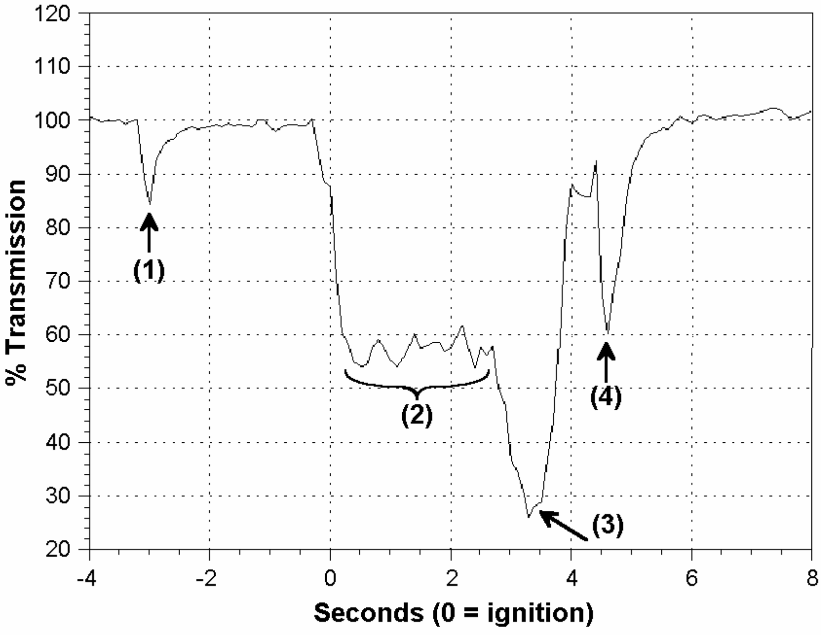

Figure 1. Plot of a single wavelength measurement of percent transmission.

helium-neon (HeNe) laser line and the 488 nm argon ion (Ar^+) laser line, demonstrated the ability of a laser based opacity system to accurately follow the stages of a typical rocket firing at the UALR HRF.

While the dual wavelength system also demonstrated spectral variations in plume opacity, it was not capable of providing concrete information about the nature of the particulate matter. Results from the study did not fit the expected absorbing characteristics of soot particles, but instead indicated the possibility that the particulate matter in the hybrid rocket plume was of a non-absorbing optical nature.

The current work, with a total of seven laser lines for measurement instead of two, sought to extract further information about the optical and physical properties of the plume particulates.

Rocket Plume Opacity

In both the prior and current studies, the stages of a rocket firing sequence are well defined. For reference, a plot of a percent transmission (%T) trace from a single wavelength measurement is shown in Figure 1, and a corresponding description of the stages in a rocket firing follows:

1) At $\tau = -3$ seconds ($\tau = 0$ is the time of motor ignition) oxygen flow to the motor is started. This sudden rush of high pressure oxygen blows out whatever dust or soot is left in the fuel grain from grain manufacture or a previous motor firing. This puff of dust, readily visible to the naked eye, momentarily occludes the probe beam, providing a consistent time marker for the start of the firing cycle.
2) At $\tau = 0$ seconds, the igniter flashes and the fuel grain ignites. The plume opacity increases (%T decreases) as the motor climbs to a steady burn condition, during which time the plume opacity stabilizes at a constant level. Fluctuations in the plume opacity during this phase of the firing are consistent with fluctuations in the rocket chamber pressure and with apparent plume brightness.
3) At approximately $\tau = 2.6$ seconds, the oxygen flow to the motor is shut down, and the motor transitions through a fuel-rich condition as the remaining oxygen in the motor bore is consumed. This sooty, fuel-rich combustion greatly increases the plume opacity. As combustion subsides, pressure in the motor chamber decreases and less smoke is emitted, causing plume opacity to decrease.

4) The last feature of the %T trace occurs at approximately τ = 4.5 seconds, when a nitrogen purge of the motor begins. At this point, smoke accumulated in the motor chamber is expelled, again causing a brief increase in plume opacity. In some cases, the motor continues to smoke for several seconds, preventing the %T trace from returning to 100% before the end of data acquisition. This is of no consequence in this work.

Experimental

Rocket and Firings

All rocket motor plume studies were carried out using the lab-scale system of the UALR HRF, a 2 × 10-inch (51 × 254 mm), gaseous oxygen system with computer control. Fuel for the firings consisted of hydroxyl terminated polybutadiene (HTPB) with 1% by weight graphite additive, a standard fuel grain formulation used at the UALR HRF. Five firings were run at an oxygen mass flow of 0.06 lbm/s to assess the repeatability of the measurements. An additional 14 firings were run with oxygen mass flows between 0.04 and 0.13 lbm/s, giving a variety of conditions. Pressures during these firings were typically held between 200 and 500 psi. Additional details of the rocket and its feed and control systems can be found in previous papers.[4–6]

Apparatus

The experimental apparatus consists of two laser sources, optics for beam collineation and positioning, a spectrograph with photodiode array (PDA) detection, and a portable computer for data acquisition. A diagram of the system is shown in Figure 2.

Probe Beam

The probe beam is constructed by collineating the beams from two lasers. The first laser is a Spectra Physics model 162A-07 Ar$^+$ laser powered by a model 262 Exciter. The model 162A-07 is a single-line laser with a high reflectance Littrow Prism for line selection; however, for this work, the prism was replaced with a Melles Griot Extended MAXBRIte^{TM} mirror. This produced an output beam consisting of the

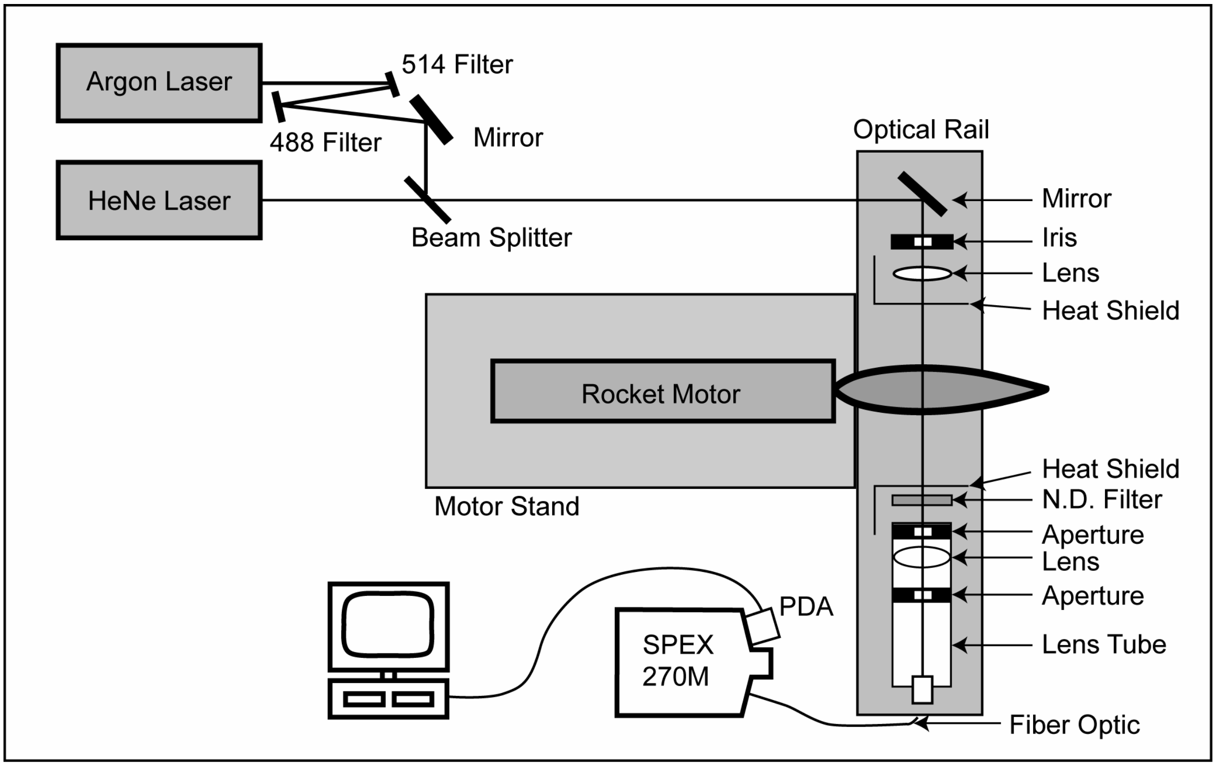

Figure 2. Diagram of opacity measurement system.

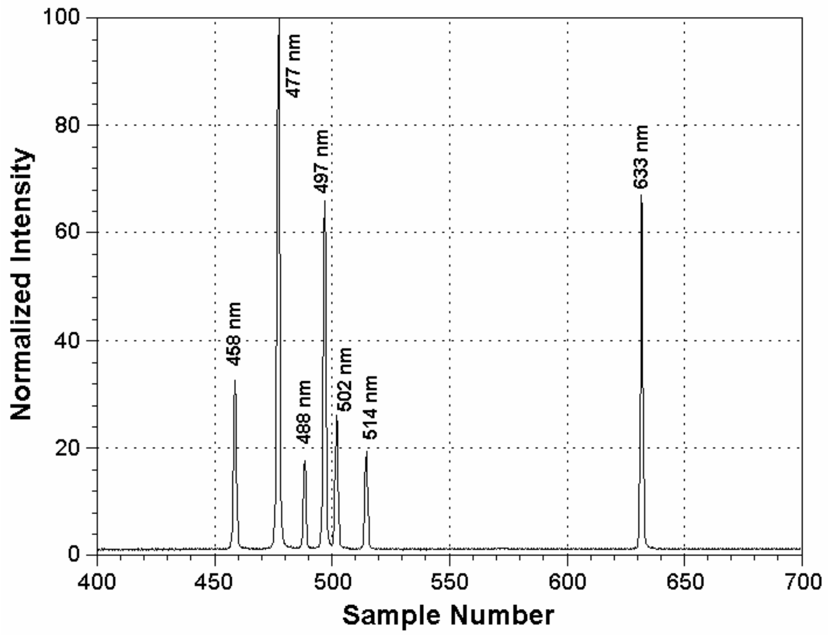

Figure 3. Relative intensities of the laser lines.

following laser lines (rounded to the nearest whole nanometer): 458, 477, 488, 497, 502, and 514 nm. The total power in the Argon laser beam was adjustable to 60 mW.

The 488 and 514 nm lines are more than an order of magnitude stronger than the 502 nm line. This presents a potential problem with the dynamic range of the detector, so line pass interference filters were used as mirrors to reduce the intensity of the 488 and 514 nm lines. While this greatly reduced the total power of the multiline beam, the power was more than sufficient for this work.

The second laser is a Siemens LGK 7626 HeNe laser with an output power of 20 mW. A neutral density filter is used to attenuate the HeNe laser output to match the final level of the Ar^+ laser beam. The HeNe laser beam is combined with the Argon laser beam using a 50/50 beam splitter, as illustrated in Figure 2. A plot of the relative line intensities in the probe beam is shown in Figure 3.

Optics

After the two laser beams are combined, the resultant probe beam is directed to an optical rail mounted at the rear of the rocket motor. A mirror redirects the beam in a direction perpendicular to the motor axis. After passing through an iris used for alignment reference, the probe beam is focused through the plume with a 60 cm focal length lens. After passage through the plume, the probe beam is attenuated by a neutral density filter to cut it to a level suitable for PDA detection. The beam then passes through a 2.5 mm aperture into an enclosed lens tube. Inside the lens tube, the beam is focused by a 25 mm focal length lens through another 2.5 mm aperture. The resulting expanded beam is then incident on the input end of a fiber optic cable. This cable consists of multiple fibers that form a circular aperture at the entrance to the cable and terminate in a slit-shaped aperture at the exit end of the cable. The slit aperture end of the cable is used to couple the probe beam light into the spectrograph.

The purpose of expanding the probe beam before it enters the fiber optic cable is to insure that it completely covers the fiber aperture. If the beam were sharply focused onto the fiber aperture, it would only illuminate some of the fibers in the cable. Slight movements of the probe beam, caused by rocket motor vibrations, would change the beam entrance and exit positions, leading to changes in the detected intensity of the probe beam. Expansion of the probe

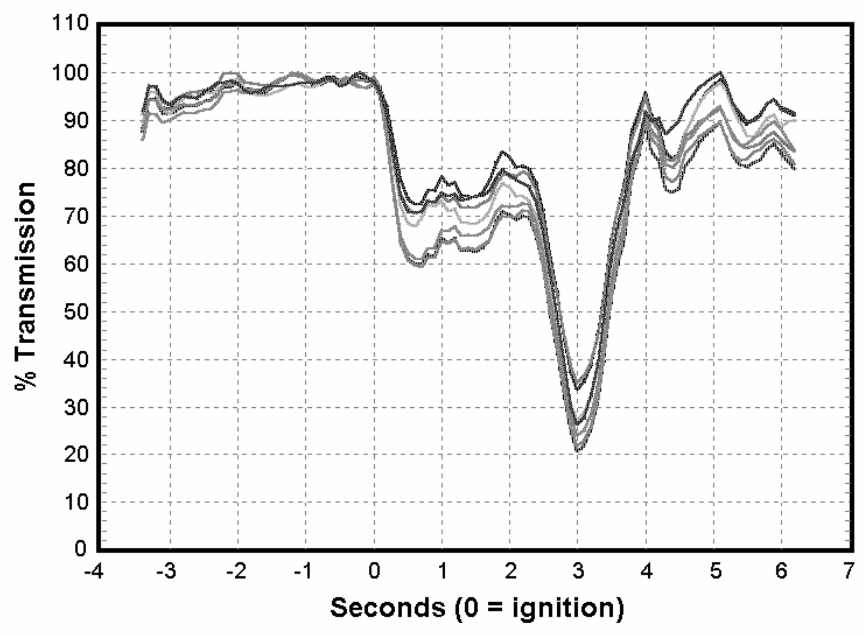

Figure 4. Percent transmission vs. time for the seven laser lines.

beam to a size that covers the fiber aperture provides more uniform illumination of the fibers, significantly reducing the effects of vibrations.

Detector

The spectrograph used in this work was a SPEX 270M with an EG&G Reticon RL1024-SAQ-011 photodiode array and RC1000LNN-011 motherboard.[7] The video output from the PDA system was read with a Computer Boards 1600 A/D converter card (12-bit resolution) in a Best Computer 386-SX portable computer running an in-house generated software package called ESPEC. A 60 µm entrance slit width and 27 ms integration time were used for all motor firings, and scans were taken at 100 ms intervals. For each motor firing, data acquisition was begun at approximately three seconds before ignition and continued for a total of ten seconds.

System Noise

After a suitable warm-up time, the signal from the PDA, with no probe beam, was about 40 A/D counts, or slightly under 1% of full scale. Output values of pixels not corresponding to laser wavelengths remained around the 40-count level during motor firings, indicating essentially no response to optical noise from the plume. There were some fluctuations in the measured intensities of the laser lines, however. The fluctuation levels of all but the 477 nm line were at or below ±4%, while the fluctuations of the 477 nm line were ±9%. A moving average with a bin width of 0.3 seconds was applied to the data during processing, reducing the above figures to ±3% and ±7%, respectively.

Data Analysis

Each data file from a rocket firing consists of A/D counts for 100 scans of 1024 pixels each. The data analysis was performed with software written for the project, and run in Windows95 on a Pentium PC. For each scan, the software finds the pixels corresponding to the seven laser lines and finds the value of these peaks. The software then applies a moving average (0.3 second bin width) to the data and creates seven data plots of A/D count as a function of scan number, one plot for each of the laser lines. Next, the A/D count value that corresponds to 100% T for each laser line is calculated from the portion of the data before motor ignition. A time scale is then calculated from the data scan numbers, and %T as a function of time is plotted for the laser lines. A typical plot is shown in Figure 4.

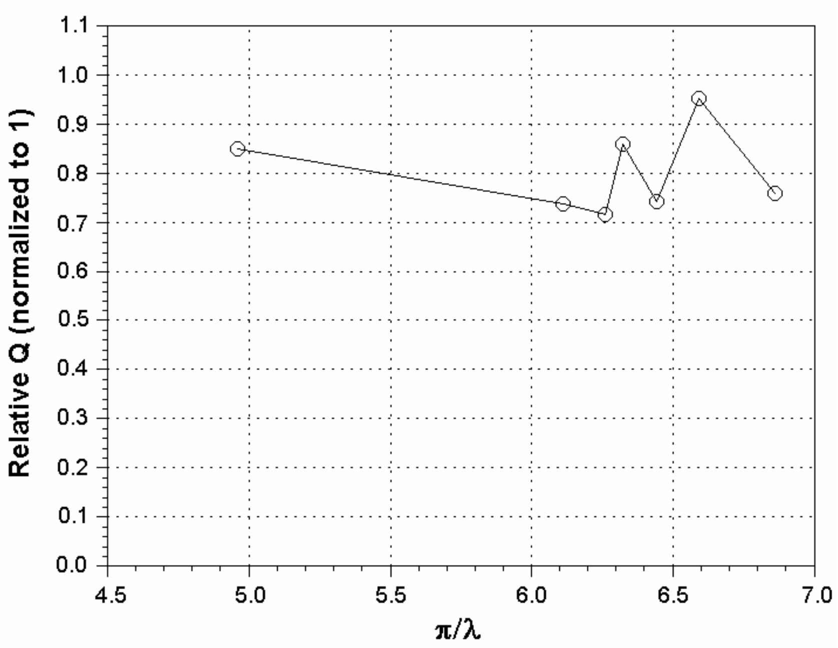

Figure 5. Average of the relative scattering coefficients for five firings at 0.06 lbm/s oxygen flow.

In order to compare the opacity measurement results to Mie scattering curves, the relative scattering coefficients (Q) for the seven laser lines must be calculated. Ratios of Q values can be obtained from %T as follows:

Transmittance (T) is defined[1] as

$$T = \frac{I}{I_0} = \exp\left[-naQt\right] \qquad (1)$$

where,

I = light intensity transmitted through the plume

I_0 = light intensity with no plume

n = number of particles per unit volume

a = cross sectional area of a particle

t = path length through the plume

Taking the natural logarithm of both sides of equation 1 yields

$$\ln T = -naQt \qquad (2)$$

Correspondingly, for two measurement wavelengths,

$$\ln T_1 = -naQ_1t \qquad (3)$$

$$\ln T_2 = -naQ_2t. \qquad (4)$$

Dividing equation 3 by equation 4 and canceling like terms yields

$$\frac{\ln T_1}{\ln T_2} = \frac{Q_1}{Q_2} \qquad (5)$$

The relative scattering coefficients are calculated from the natural logarithm of transmittances and normalized by setting the highest Q equal to one. Plots of scattering coefficients are often plotted as a function of particle size parameter (α) that is given by

$$\alpha = \frac{\pi d}{\lambda} \qquad (6)$$

where,

d = particle diameter

λ = the wavelength of light in the medium

The relative Q values are calculated from the average T exhibited by each laser line during the steady state burn portion of the firings. Since the particle diameter is not known, the relative Q values are plotted against π/λ, as shown in Figure 5. These plots are then compared to published plots of scattering coefficients, as predicted by Mie scattering theory. A sample of such plots is shown in Figure 6.

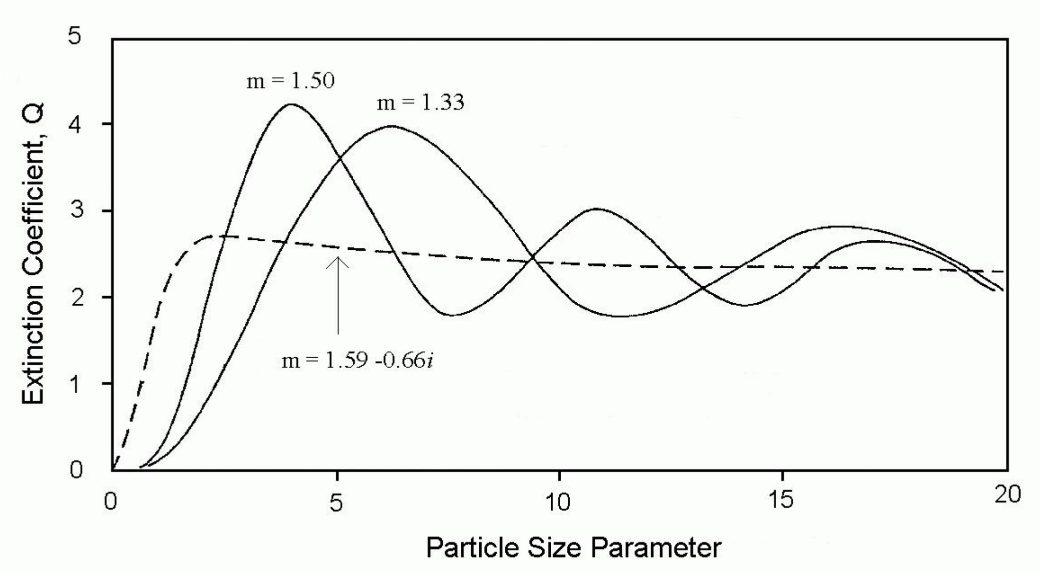

Figure 6. Typical plot of extinction coefficients from Mie calculations. The dashed line is characteristic of absorbing particles, while the solid lines are characteristic of non-absorbing particles.

Results and Discussion

From Figure 6 it is apparent that *Q* decreases monotonically with increasing α for absorbing particles, and that *Q* oscillates with decreasing magnitude as α increases for non-absorbing particles. The plots for non-absorbing particles in Figure 6 indicate the general trend followed by *Q* values for these particles, but they do not reveal the additional fluctuations that are typical of non-absorbing particles.[1] Though it was expected that the particulate matter in the hybrid plume would consist of absorbing soot particles, the relative scattering coefficients do not follow a pattern consistent with that of absorbing particulate matter. Instead, the data suggests that the hybrid plume particulates may be primarily non-absorbing in nature. An investigation of the validity of the data led to the following observations.

Although the laser lines in the probe beam exhibited random fluctuations, the fluctuations in the *Q* values for this work cannot be the result of such random noise. The data in Figure 5 is an average of the relative *Q* values for the five rocket firings that were conducted at 0.06 lbm/s oxygen flow rate. If the fluctuations were due to random noise, they would have, at least partly, averaged out. Furthermore, almost all of the data runs exhibited relative *Q* values that followed the same general oscillatory pattern. For this reason, the oscillations are accepted to be resultant from the optical nature of the plume.

One possible explanation for the *Q* oscillations is a lensing effect from the heat of the plume, causing beam steering. The plume can approximate a cylindrical lens, since it has that shape and the hot gases are of a different refractive index from the surrounding atmosphere. However, this explanation is unlikely for two reasons:

1) A lensing effect would affect the laser lines in a more or less monotonic manner (i.e., the effect would not be so radically variant with wavelength).
2) The probe beam was centered in the plume cross-section to within 0.5 mm, minimizing any lensing effect that might occur if the probe beam were off-center.

It is not expected that the *Q* variations in the data are due to beam steering effects.

At this time, it is impossible to know exactly what the *Q* fluctuations indicate about the plume particulate characteristics, but they may well be part of the fluctuations in curves for normal, non-absorbing particles. A rigorous regression analysis of the data to fit Mie scattering theory would provide more information. Such an approach has been used with some success in measuring aluminum oxide (Al_2O_3) particulates in the plumes of solid rocket motors.[8]

Conclusions

Results from this study and the previous measurements conducted with the dual wavelength system suggest the presence of non-absorbing particulate matter in the hybrid rocket plume. While the exact nature of this matter cannot be determined by these methods, the data seem to show that aerosol droplets of some nature exist in the plume. These droplets can only have come from the fuel-grain polymer material, and strongly indicate that the fuel goes through a melt stage, at least partially, during the burn process. This is not in agreement with the presently accepted model that the fuels pyrolyze through a charring process. If this is true, the actual combustion process likely consists of both charring and melting of the polymer fuel, and it may explain some of the combustion instabilities that exist (pressure pulsing, etc.) for the hybrid class of rocket motors.

Certainly, this multi-wavelength system provides more detailed plume particulate information than the dual wavelength system. Current efforts to improve overall system performance are focused on enhancing laser line stability, including additional spectral lines, and on developing the computational tools for calculating extinction coefficients and fitting data to Mie scattering models.

Acknowledgments

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