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GAS TEMPERATURE AND CONCENTRATION MEASUREMENTS IN THE VICINITY OF A BURNING/DECOMPOSING CARBON-EPOXY AIRCRAFT COMPOSITE MATERIAL

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We report measurements of temperature and O_2/N_2 mole-fraction ratio in the vicinity of a burning and decomposing carbon-epoxy composite aircraft material samples exposed to uniform heat fluxes of 48 and 69 kW/m^2. Controlled laboratory experiments were conducted with the samples suspended above a cone-type heater and enclosed in an optically accessible chimney. Noninvasive coherent anti-Stokes Raman scattering (CARS) measurements we performed on a single-laser-shot basis. The CARS data were performed with both a traditional point measurement system and with a one-dimensional line imaging scheme that provides single-shot temperature and O_2/N_2 profiles to reveal the quantitative structure of the temperature and oxygen concentration profiles over the duration of the 30-40 minute duration events. The measured near-surface temperature and oxygen transport are an important factor for exothermic chemistry and oxidation of char materials and the carbon fibers themselves in a fire scenario. These unique laser-diagnostic experiments provide new information on physical/chemical processes in a well-controlled environment which may be useful for the development of heat- and mass-transfer models for the composite fire scenario.

INTRODUCTION

Carbon-fiber composite materials have seen increased use as structural components of both military and civilian aircraft. Heat fluxes from composite-fueled structure fires can reach several hundred kW/m^2 so that this class of materials represents a significant risk to assets and personnel. Composite materials thus represent a new fire-accident scenario from which assets must be protected. A detailed review of carbon-epoxy composite fire behaviour has recently been provided by Brown.[1] Fire and materials testing of composites has been performed for both intermediate-to-large scale structural test environments[2, 3] and using laboratory instruments[4, 5], and these studies have identified multiple combustion pathways which must be firmly understood for engineering risk assessments. Combustion likely begins as the heat flux from an aviation fuel fire, or other source results in thermal decomposition of the binder, which then readily ignites the composite structure fire. Carbon fibers within the matrix then undergo charring, which can insulate remaining binder and fibers from combustion. Oxygen transport to the composite surface is a critical factor, as char layers can be consumed to reignite remaining binder materials and ultimately sustain burning of the carbon fibers themselves. These surface oxidative reactions may be highly exothermic, and can increase heat fluxes substantially making them a critically important factor for risk assessment.

The purpose of this study is to perform detailed measurements of temperature and oxygen transport near the surface of an aircraft-grade carbon/epoxy composite material under imposed radiative fluxes sufficient to achieve autoignition of the sample binder material. Experiments have been performed in a well-controlled laboratory setting, and a laser-based spectroscopic probe, coherent anti-Stokes Raman scattering (CARS), was used to perform high-fidelity, non-invasive and simultaneous measurements of temperature and O_2 content. Both point measurements and one-dimensional spatial profile measurements were performed on an instantaneous basis, and we present two representative experiments at heat fluxes of 48 and 69 kW/m^2 here. CARS measurements are free of thermal inertia effects associated with physical probes, delivering essentially infinite (picosecond) temporal response, with a spatial resolution of order 10^{-5} cm^3. These optical measurements are additionally free of insertion, radiation and conduction errors which plague thermocouple measurements that are often used in fire testing.

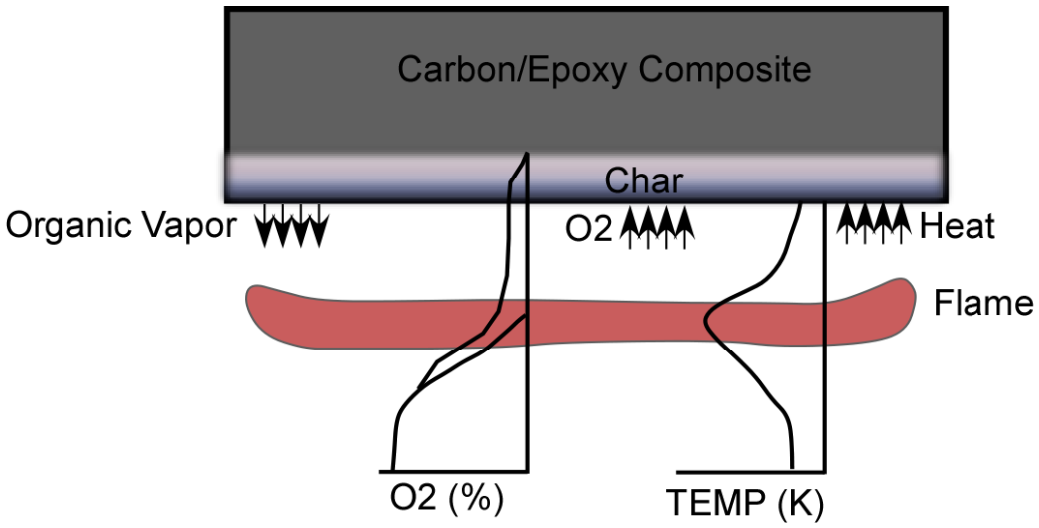

Figure 1. Conceptual drawing of controlled composite burn experiment: a uniform radiative heat flux is supplied to the lower surface of the carbon/epoxy composite sample, which then decomposes, chars, and burns after autoignition. CARS measurements are performed on the underside of the sample to investigate the structure of the temperature and oxygen distributions near the sample surface.

CONTROLLED COMPOSITE BURN EXPERIMENTS

The experiments were conducted in a controlled manner with a uniform heat flux applied to planar HEXEL 3501-6 carbon-epoxy composite samples that were oriented horizontally. The samples were 3-mm thick and 100-mm × 150-mm in cross section. A conceptual scheme of the composite burn experiment is given in Figure 1. Heat flux was supplied to the lower surface of the samples by a cone-type heater that is typical of fire response testing of materials. The samples were suspended 25.4 mm above the surface of the cone heater by simply resting their 100-mm edges on top of 6.35-mm diameter steel optical posts. The top side of the sample was insulated using a 25.4-mm-thick slab of FIBERBOARD insulation. The cone-heater/sample assembly was then enclosed within a sheet-metal chimney with 125-mm-diameter windows on three sides to provide optical access for both visual inspection/photography and for the CARS laser diagnostics used for the temperature/oxygen measurements. The chimney was 762 mm mm in height, with a 610-mm square cross section, and was fully open at its bottom. Two steel-mesh screens were placed across the open chimney top to isolate the burn experiment from air currents both within the room and induced by the ventilation hood used to remove heat and combustion products from the laser laboratory. Digital photographs of the test assembly that show the position of the heater, mounting posts, and sample assembly are provided in Figure 2.

A 150-mm diameter cone heater (GBH International) was specified by the manufacturer to provide a uniform heat flux over the center 100-mm portion of the heater surface. Heat flux as a function of heater temperature was characterized using a thermopile-type sensor positioned over the center of the heater exit plane, with the resulting calibration data displayed in Figure 3. At the 25-mm sample height above the heater exit plane used for our experiments, the heater was capable of providing fluxes over 100 kW/m^2, well in excess of the 31.5 kW/m^2 critical value identified by Quintiere *et al.*[5] for autoignition of similar carbon-epoxy aircraft materials. Experiments were conducted at heater temperatures of T = 600, 700, 800, and 900 °C, corresponding to sample heat fluxes of q'' = 32−90 kW/m^2. Representative measurements at q'' = 48.5 and 68.8 kW/m^2 are presented here.

Temperature/oxygen measurements were made in the vicinity of the burning composite samples using two types of CARS instrumentation, which are discussed in more detail below. Point measurements were performed at Sandia/NM. For these point measurements, the sample/burner/chimney assembly was placed on a motorized positioning system and the sample was translated vertically during the measurements. These point measurements were conducted at an acquisition rate of 1 kHz, so that a large number of temperature/oxygen samples could be collected during the 20-30 minute experiments; however, the spatial correlation of these instantaneous point measurements was uncertain because the full spatial

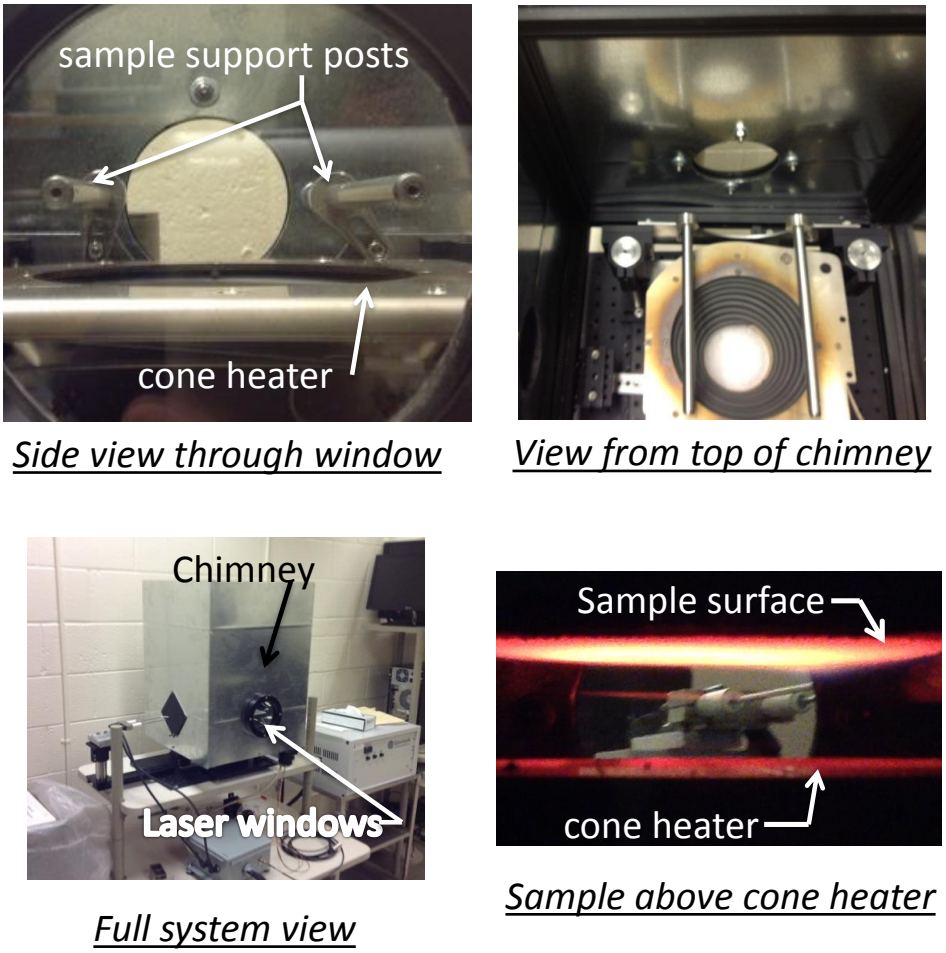

Figure 2. Digital photographs of cone-heater, composite sample, and chimney assembly used in burn experiments.

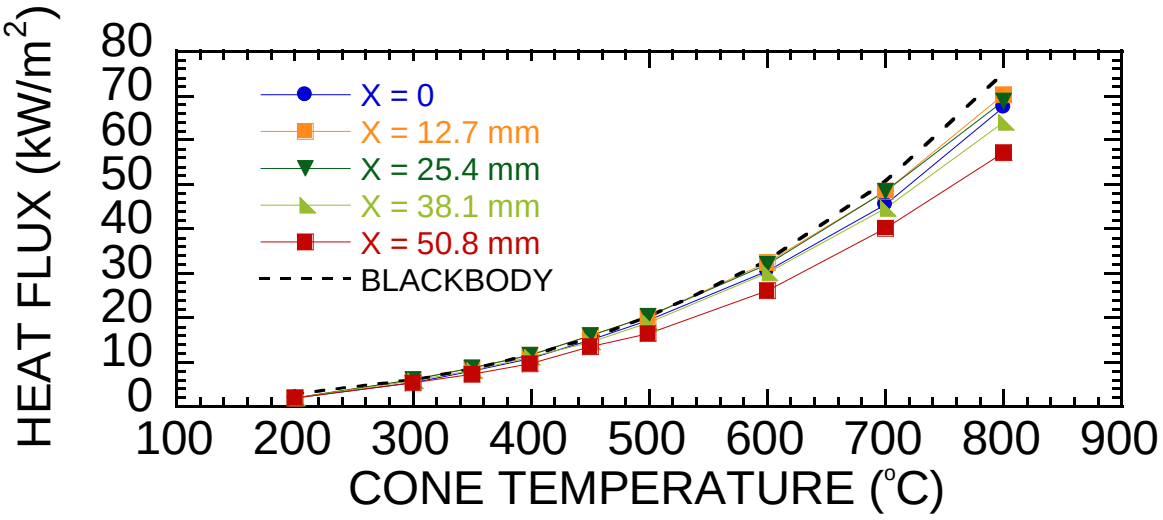

Figure 3. Heat flux, as measured by a thermopile, at cone-heater center as a function of heater temperature and height above the heater surface.

profiles could not be obtained on a single-laser-shot basis. An improved picture of the surface-normal spatial distribution of temperature and oxygen was obtained using a CARS setup at Sandia/CA, where full 1-D profiles could be recorded along a 1-D line. These measurements were conducted at a reduced data rate of 20 Hz.

CARS INSTRUMENTATION

Temperature and O_2/N_2 mole-fraction ratio measurements were performed using a hybrid femtosecond/picosecond CARS scheme. A detailed treatment of the CARS technique is given in an excellent review by Roy *et al.*[6], while in-depth descriptions of the point[7] and 1-D line-imaging[8] CARS systems used here are also provided in the literature. An abbreviated description that illustrates the basic conduct of our CARS measurements and the sensitivity of CARS spectra to temperature and oxygen content is provided alongside the experimental results to be presented below. CARS is a laser spectroscopic technique in which rotational or vibrational Raman spectra of combustion molecules are generated with an intense laser-like signal as shown for point (upper) and line-imaging (lower) measurements in Figure 4. In the present implementation, two photons from a broadband, 800-nm, femtosecond-pulsed Ti:sapphire laser (shown as red laser beams in Figure 4) prepare a rotational Raman coherence that is then probed at a short (10-300 ps) time delay later by a picosecond-duration, bandwidth-limited visible (400 nm or 532 nm) laser pulse (shown as blue or green in Figure 4). The CARS signal emerges as a coherent laser-like beam that is shifted from the probe laser optical frequency by 10−300 cm^{-1}. A grating spectrometer disperses the signal beam and CARS spectra are detected on a single-laser-shot basis with a charge-coupled-device (CCD) camera. Contributions from N_2 and O_2 dominate the CARS spectra acquired here. These spectra are analyzed for temperature and O_2/N_2 mole-fraction ratio by performing least-squares fitting of the measured spectra to the theoretical model described by Kearney.[7]

Point measurements were conducted at the Engineering Sciences Experimental Facility at Sandia/NM using the concept shown at the top Figure 4. Preparation pulses were provided by two separate 800-nm laser beams, shown in red, which crossed the 400-nm 5-ps-duration probe beam (shown in blue) at the focus of a beam-crossing lens. All laser beams propagated in a direction parallel to the sample-support posts shown in Figure 2 so that the laser beams could be brought as close to the composite sample surface as possible. The CARS signal beam, shown in violet, was generated within a beam-overlap region at the lens focus, best described as an ellipsoid with ~100-μm minor axis and ~1.5-2.0 mm major axis,

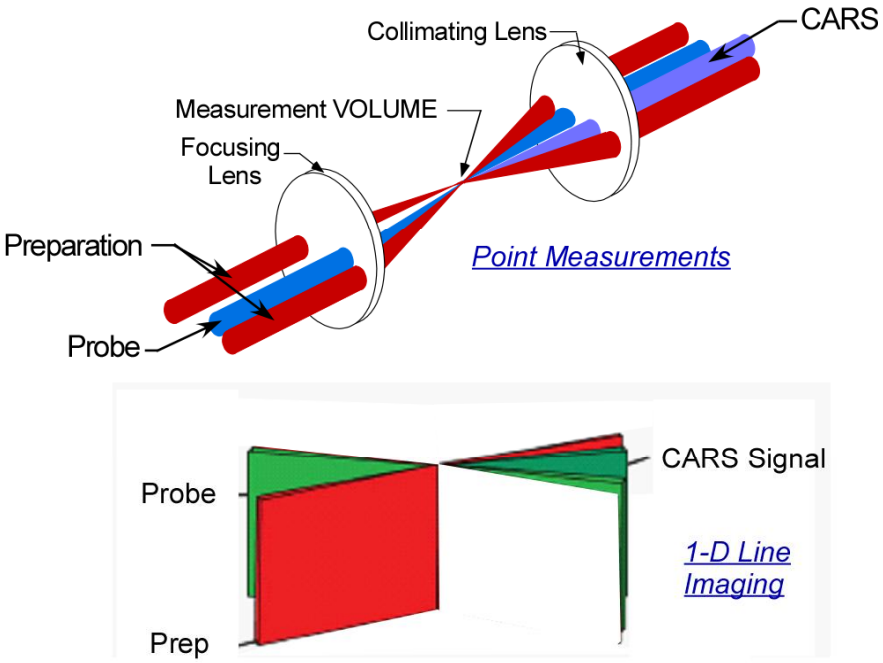

Figure 4. Illustrations of the preparation, probe, and CARS laser beams used for point measurements (above) and 1-D line-imaging measurements (below).

with the minor axis oriented normal to the sample surface. The temporal resolution of this point imaging scheme was 20 ps, which is essentially infinite for fire and combustion processes. CARS spectra were detected at the laser repetition rate of 1 kHz with this arrangement.

The point measurement scheme delivered high-data-rate quantitative measurements, but spatial profiles were difficult to obtain as a result of continuous deformation of the sample surface during the measurements. To obtain an improved picture of the structure of these spatial profiles, a second set of measurements was made at the Combustion Research Facility and Sandia/CA using the 1-D line imaging scheme shown in the lower portion of Figure 4. Line imaging CARS enabled temperature and O_2/N_2 profiles normal to the surface to be obtained on a single-laser-shot basis, albeit at a reduced data rate of 20 Hz. Preparation pulses were provided by a similar femtosecond Ti:Sapphire laser used for point measurements, while a 90-ps probe pulse was supplied by a 532-nm Nd:YAG laser which delivered the increased energy necessary to generate detectable CARS signal along a line. The red and green laser beams were focused in the horizontal axis only using a cylindrical lens, so that their crossing formed a vertical line that was ~ 12-mm high. A combination of cylindrical and spherical lenses was used to relay image the beam-crossing line at unit magnification onto the entrance slit of a grating spectrometer, so that the vertical integrity of the beam crossing plane was maintained on the CCD vertical dimension with spectral dispersion along the horizontal axis of the detector. With this scheme, a series of 50-75 CARS spectra could be obtained on a single laser shot by sampling the detector images along horizontal lines. Spatial resolution normal to the sample surface was determined by the ~50 μm diffraction-limited blur of the relay imaging optics, while the horizontal extent of the beam crossing region was estimated to be ~1 mm.

Measurement uncertainty for the hybrid fs/ps CARS scheme used for the point measurements was recently assessed in H_2/air and C_2H_4/air flat flames [7], where the accuracy of the temperature data was found to be 3−5% with a precision of 1−2%. For O_2/N_2 mole ratio in excess of 6%, the accuracy of the O_2/N_2 measurements was 5−10%, with a precision of 1−2%. At lower O_2/N_2 values, accuracy degraded to 40% by O_2/N_2 ~ 2%, and the detection limit for O_2 with this technique is likely on the order of O_2/N_2 = 1−2% by mole. Uncertainty in the 1-D line imaging measurements was degraded to an unknown extent as a result of imaging the beam-crossing region through thermally induced turbulence, which introduced some aberrations into the measured CARS lineshapes.

RESULTS AND DISCUSSION

Observation of sample burning characteristics

Digital photographs recorded during a composite-burn experiment with a steady-state cone-heater temperature of 973 K, corresponding to a heat flux of q'' = 48.5 kW/m^2, are shown in Figure 5. These images illustrate the qualitative feature all composite-burn experiments conducted in this series. The experiments were started by ramping the cone-heater temperature from room conditions to the steady-state heater setpoint. During the ramp, sample delamination and accompanying outward deformation, or "bowing" of the lower sample surface, was visually observed as the heater temperature ramped through 823−873 K, or a heat flux of q'' ~ 24−31 kW/m^2. Sample deformation was immediately followed by the vigorous emission of white smoke from the sample, presumably as a result of rapid thermal decomposition and outgassing of the binder material. Autoignition of the samples occurred a short time later (within 10 seconds) at a heater temperature near 923 K, corresponding to a heat flux of q'' ~ 37.7 kW/m^2—a value that is consistent with the critical heat flux for autoignition of q'' = 35 kW/m^2 reported by Quintiere *et al.*[5] in their laboratory scale experiments.

Following autoignition, the burning of the composite samples could best be characterized in three phases: (1) a heavily sooting phase; (2) a "flickering" combustion phase; and (3) a late-time phase. The initial 60-90 seconds following autoignition were characterized by a heavily sooting flame that covered the lower surface of the composite sample, with flames additionally emerging from the sample edges, as shown on the uppermost panel of Figure 5. Soot volume fraction during this early burning phase was high enough that the CARS laser beams were often completely absorbed, and no CARS signal could be measured until the later-most portions of this sooting phase. Particulate formations that were large enough to be seen by eye were additionally present during this heavily sooting phase. Following the initial sooting phase, a flickering combustion phase where isolated pockets of orange-yellow flame travelled across the lower sample surface persisted for an additional 60-120 s. The end of sooting combustion likely resulted

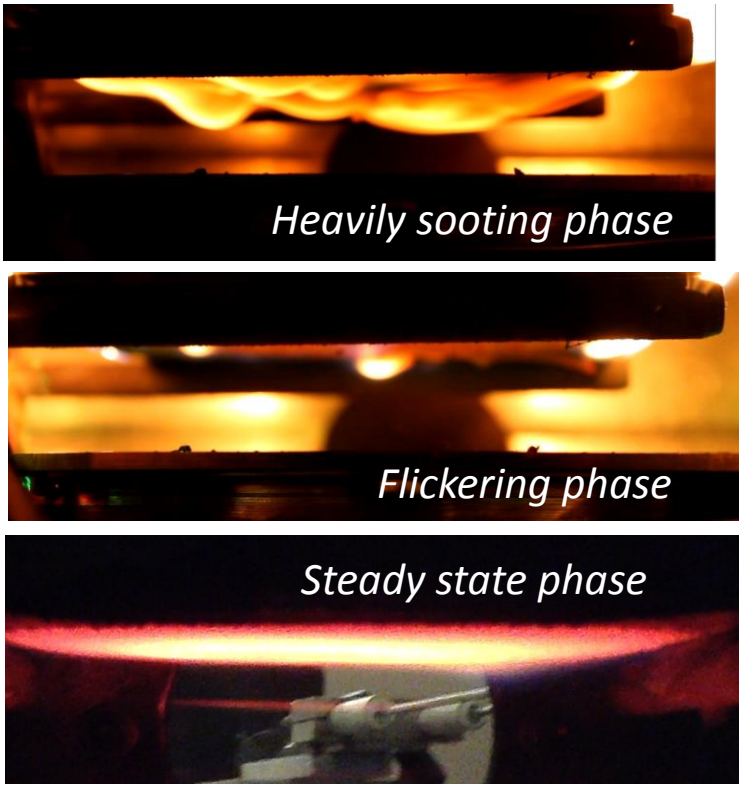

Figure 5. Still photographs extracted from video of a carbon-epoxy composite burn experiment at various times after autoignition.

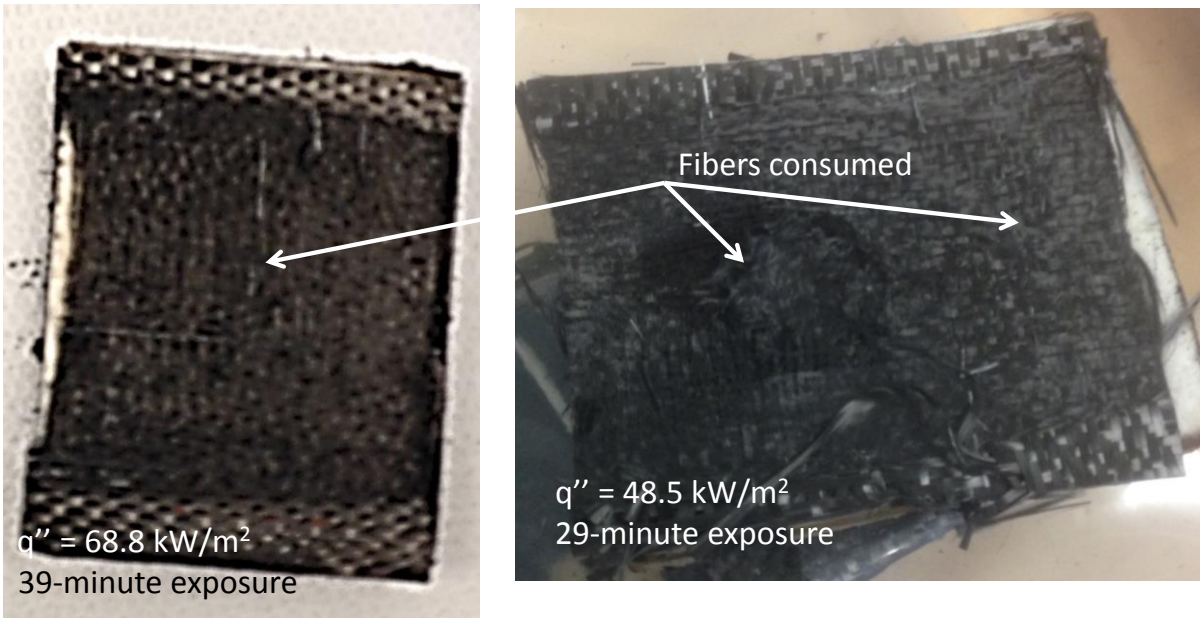

Figure 6. Photographs of post-mortem composite samples.

from nearly complete consumption of the epoxy binder. The role of char formation in the end of sooting combustion is not certain, and some isolation of the matrix could have been provided by char; however, very little, if any, binder was observed in post-mortem samples, as shown in Figure 6. The appearance of isolated sooting pockets eventually ceased, and a late-time phase ensued where a blue, presumably CO/air flame was observed to meander about the lower sample surface. Weaker yellow-orange flame emission from soot was additionally observed during the late-time steady state phase, which lasted for the duration of the nominally 30-40 minute experiments.

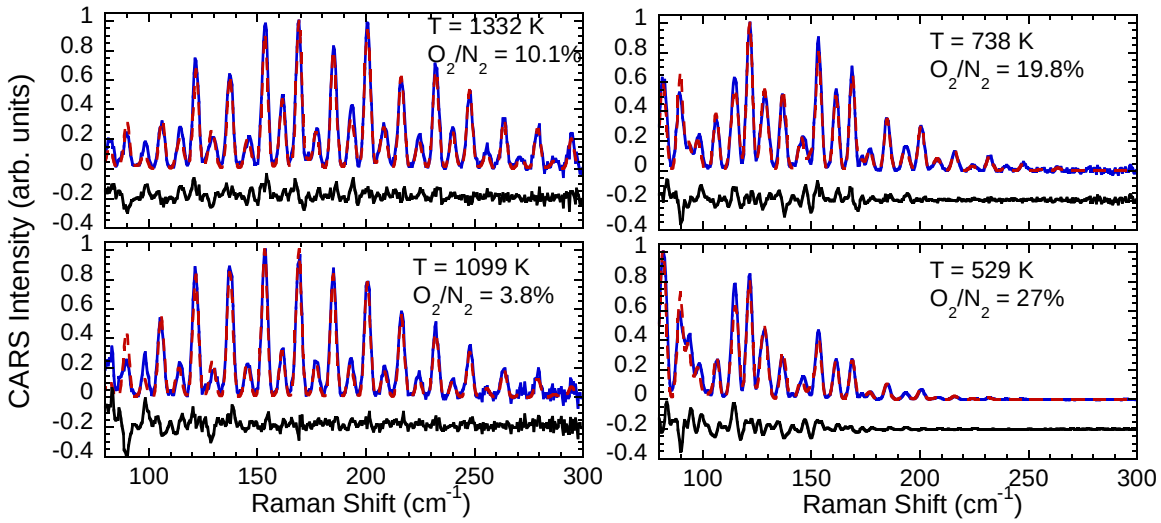

Figure 7. Representative single-laser-shot CARS spectra obtained via point measurements near the surface of a burning carbon-epoxy composite sample. Measured spectra are indicated by blue lines; best-fit theoretical spectra are shown as red dashed lines; residual – 0.2 is plotted as black lines. Cone heater temperature was 1073 K, corresponding to a heat flux of 68.8 kW/m^2.

Point CARS Measurements

Point CARS measurements were performed at a cone-heater temperatures ranging from 973−1273 K. Sample results obtained at a heater temperature of 1073, corresponding to a heat flux of $q'' = 68.8$ kW/m^2, are discussed here. A digital photograph of the post-test sample, recorded after a 39-minute exposure the applied heat flux, is shown on the left-hand side of Figure 6. The CARS measurement volume was positioned near the center of this sample, where the photograph reveals a different texture than observed near the upper and lower edges, where the sample support posts provided some shielding from the radiative flux and some epoxy binder material remained. The center portion of the post-mortem sample was readily bendable, indicating that the epoxy binder was fully consumed during the experiment, while close-up inspection of the sample indicated recession of the surface and loss of carbon fiber mass. Similar experiments at even higher heat fluxes, to be presented elsewhere, burned completely through the fibers.

Representative single-laser-shot CARS spectra obtained near the sample surface with the pointwise CARS instrument are presented in Figure 7. Measured CARS spectra (blue lines) are plotted against the least-squares best-fit theoretical predictions (dashed red lines), with the residual (black lines) offset by 0.2 toward the bottom of the plots for clarity. In general, the CARS intensity shifts toward higher lying rotational states (higher Raman shifts) as the temperature increases. Oxygen sensitivity is provided by the modulation of the overall intensity envelope formed by the peaks. The spectra on the left-hand side of Figure 7 were recorded from high-temperature regions. At lower left, the fitted temperature is $T = 1099$ K, with a relatively low oxygen concentration of $O_2/N_2 = 3.8\%$ by mole, and this spectrum exhibits a smooth peak-intensity envelope associated with spectra that are almost fully dominated by the N_2 contribution. At upper left, the temperature is even higher at $T = 1332$ K, with a higher O_2/N_2 ratio of 10.1% that results in a much more jagged variation in the observed peak intensities. Lower temperature spectra were selected for the right-hand side of Figure 7. The spectrum at the lower right-hand side is indicative of heated air at $T = 529$ K and O_2/N_2 of 27%, close to the known value of 26.8%.

One-dimensional profiles of temperature and O_2/N_2 mole-fraction ratio were obtained in the direction normal to the sample surface by translating the heater/sample/chimney assembly vertically. The CARS measurement volume was placed as close as possible to the surface before the experiment by moving the flat composite sample downward so that the focusing CARS laser beams were just clipped by the surface. We estimate that this positioned the measurement volume to obtain a pre-burn estimate of the sample location to within ~500 μm, or ½ a beam diameter at the sample edge. Heat flux was then applied to the sample, which deformed outward and clipped the CARS laser beams, and the sample was translated

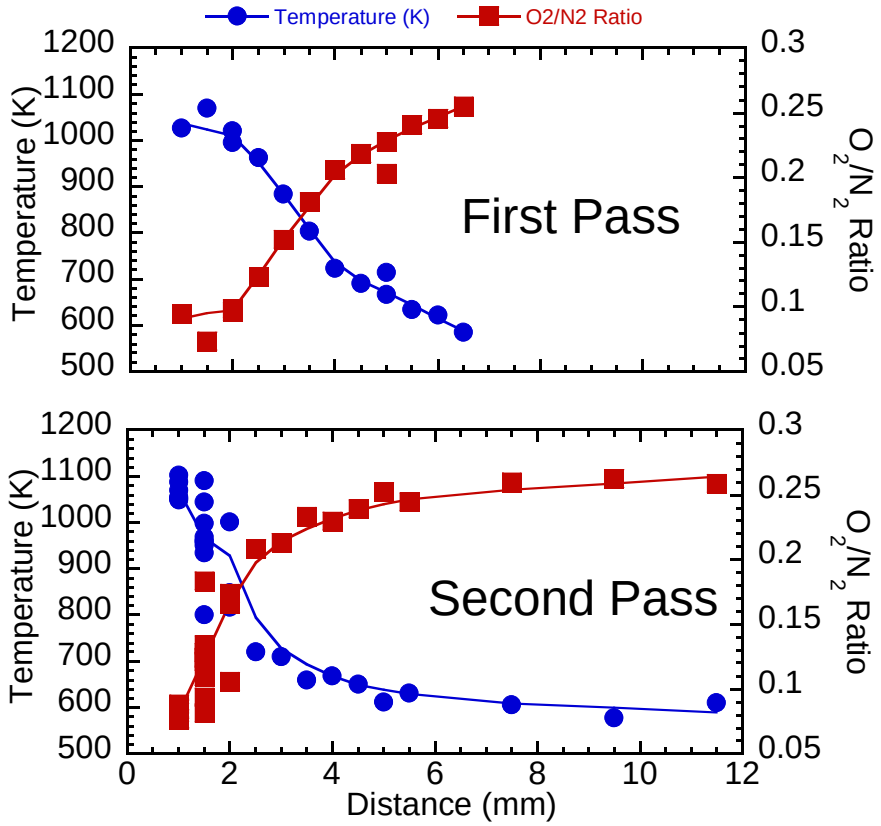

Figure 8. One-dimensional spatial profiles of mean temperature and O_2/N_2 ratio near the surface of a burning carbon-epoxy composite sample. Cone heater temperature was 1073 K, corresponding to a heat flux of 68.8 kW/m^2.

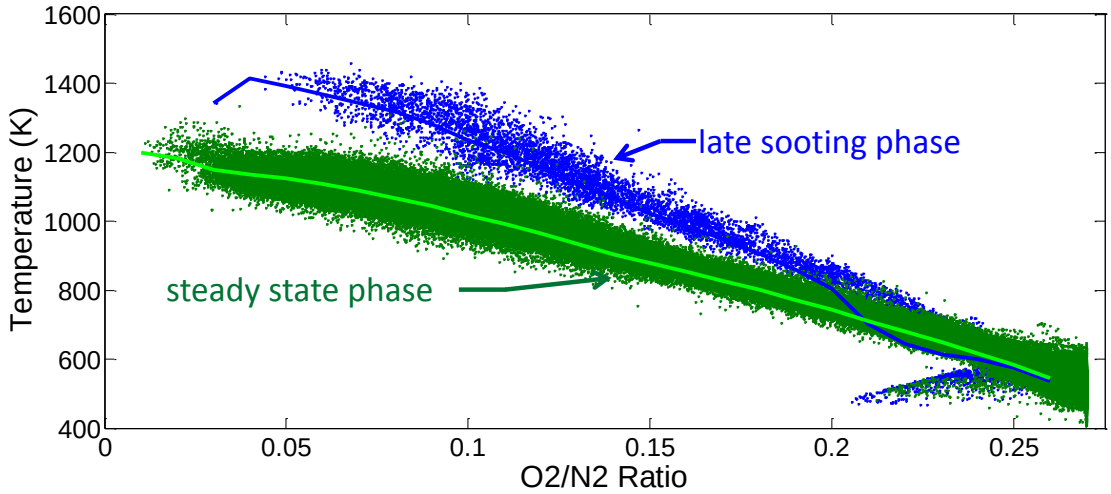

Figure 9. Scatter plots of single-laser-shot point measurements of temperature and O_2/N_2 mole-fraction ratio. The experiment was performed with a cone heater temperature of 1073 K, corresponding to a heat flux of 68.8 kW/m^2. Results in blue were obtained during the initial sooting combustion phase at a single-point approximately 4 mm from the sample. Green symbols represent data obtained throughout a region within ~ 1−12 mm of the surface throughout the duration of the steady state phase. Blue and green lines represent mean temperatures conditioned on O_2/N_2 ratio.

upward, away from the laser beams and data acquisition was started. The sample was moved progressively closer to the laser beams as 10-second (10,000 laser shots) acquisitions were performed, until the beams were ultimately clipped near the sample edge again. The sample was then moved upward again, and a second pass toward the surface was performed. Mean temperature and O_2/N_2 mole-fraction ratio profiles were obtained for each pass by averaging all valid single-laser-shot measurements at each location. The results are shown in Figure 8, where profiles for two passes made during the steady-state portion of the burn are presented. A peak temperature near $T = 1050-1100$K, close to the heater temperature of 1073 K, is obtained within 1 mm of the sample surface on both passes. At this location, significant oxygen is still present, with $O_2/N_2 \sim$ 8% on average for both sample passes. During the second pass, several 10-second acquisitions were performed close to the wall at positions of z = 1 and 1.5 mm, with several 10-second mean values reported in the lower part of Figure 8. Significant fluctuations are observed at these near-wall locations, with an average that falls near the curves that have been faired through the data points. These point measurements provide high-quality temperature and oxygen data, but with a large uncertainty in the location of the measurement volume relative to the local wall position, as the sample is consumed and the surface recesses continuously throughout the experiment. The first-pass profile has been shifted by 2.5 mm closer to the wall in preparing Figure 8 to get best agreement with the second-pass profile—a displacement that is consistent with the observed ~2.2 mm change in position for laser-beam clipping between the two passes. For this reason, the 1-D CARS line-imaging measurements to be discussed below were performed in order to obtain spatial profiles on a single-laser-shot basis.

Over the 39-minute duration of this experiment, a large number of simultaneous temperature/O_2 measurements were acquired. These single-shot data provide well-converged statistics on the overall behavior of the joint temperature/oxygen fluctuations. Scatter plots of T vs. O_2/N_2 were constructed from the large data ensemble, with the results displayed in Figure 9. The solid curves plotted on top of the single-shot measurements represent the mean temperature, conditioned on O_2/N_2 ratio. Results shown in blue represent 10,000 measurements acquired at a single-point ~4 mm from the sample surface during the later stages of the initial heavily sooting phase, during which absorption of the laser beams prevented us from making measurements any closer to the sample surface. Data shown in green represent over 400,000 single-shot measurements acquired throughout the near-wall region during the steady state phase of the experiment, where the epoxy binder has largely burned off and the carbon fibers, and/or perhaps char material, is oxidizing. The single-shot temperatures fall closely, within about ±100 K, near the conditionally averaged curves, which approximate distinct scalar state relationships for the combustion of the sample material during two distinct phases of the burn. In addition, there are no instances of zero O_2 content throughout the probed region during the steady state phase, which suggest that oxygen likely reaches the surface here even though blue and yellow flame emission could be observed during this portion of the experiment, as seen in the lower-most panel of Figure 5.

One-dimensional line-imaging CARS measurements

One-dimensional line-imaging CARS measurements were conducted at a heater temperature of 973 K, corresponding to a radiative heat flux of $q'' = 48.5$ kW/m^2. A sample single-shot 1-D CARS image acquired from the CCD camera is shown in the color contour plot at the top of Figure 10. The position imaged from the CARS beam crossing appears along the vertical, while the spectrometer's wavelength dispersion is in the horizontal dimension. Transitions in the CARS spectrum appear as vertical lines in the image, whose intensity is indicated by the arbitrary color scale. The zero position on the vertical axis represents the point closest to the sample surface where CARS signal was detected. Above zero, the sample surface has clipped the CARS laser sheets, so that the exact sample position is still uncertain. Inspection of this contour plot reveals the qualitative nature of the associated temperature and oxygen profile. Line intensities above 200 cm^{-1} Raman shift increase as the surface is approached, indicating a rise in temperature there, while intensities from now-isolated O_2 transitions decrease, showing that oxygen is consumed.

CARS spectra can be extracted from each row on the camera, and sample spectra recorded in the line-out regions indicated by purple, red, and blue dashed lines are shown below the color contour plot. The spectral resolution in the 1-D measurements is finer than in the point measurements above, as a result of the longer duration, narrow linewidth CARS probe beam employed. This increased resolution allows us to fully isolate O_2 and N_2 transitions from each other. Far from the wall, at a position of z = 2.26 mm (light

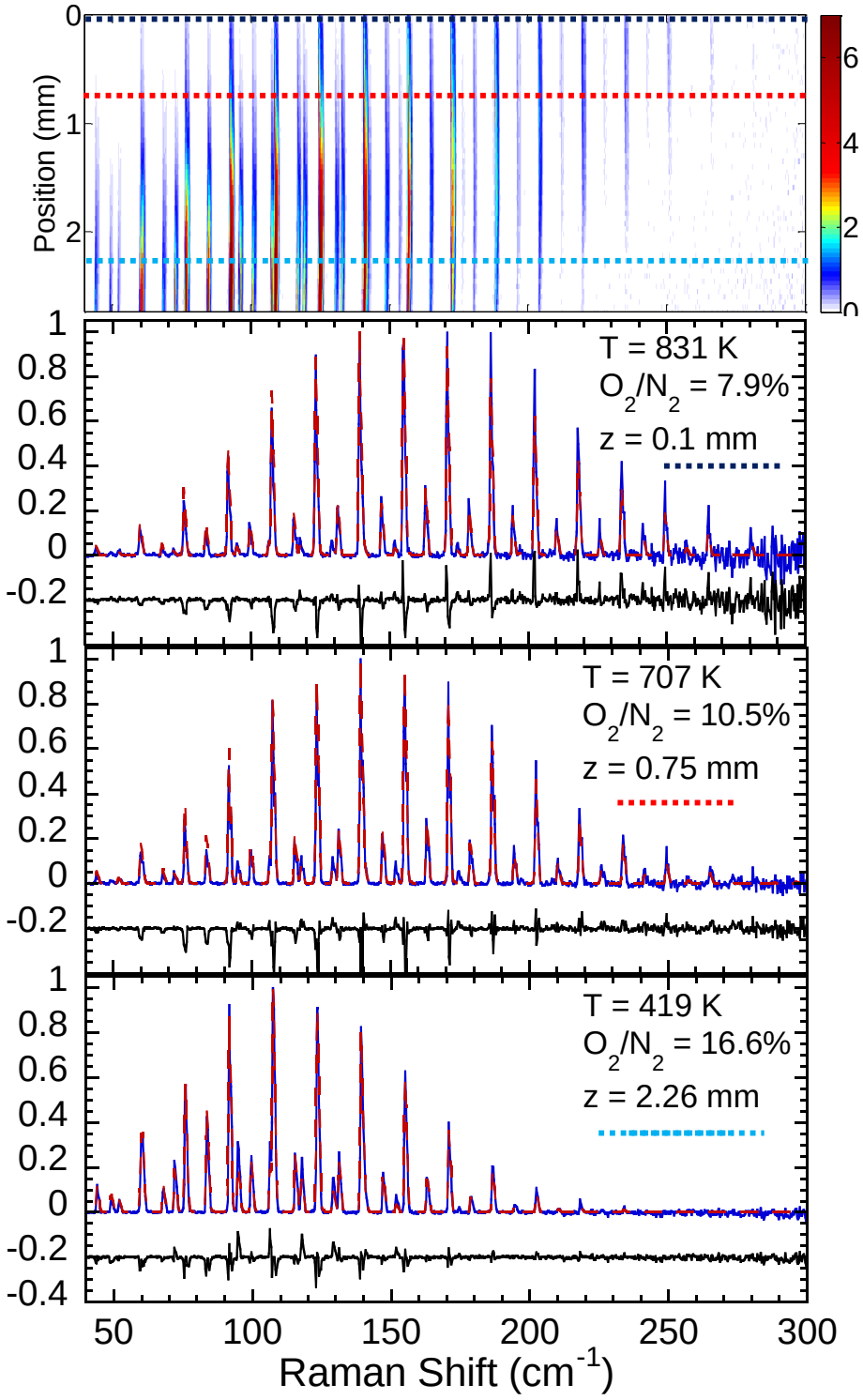

Figure 10. Representative single-laser-shot 1-D CARS imaging data obtained in the near-surface region of a carbon-epoxy composite material under a heat flux of q'' = 48.5 kW/m^2. The full image from the CCD camera is shown as a color contour plot at the top of the Figure. Three representative measured spectra (blue lines) are shown alongside best-fit theoretical predictions (dashed red lines) at the detector row positions indicated by the dashed lines drawn on the contour plot.

blue dashed line) the spectrum at the bottom of Figure 10 shows significant intensity in isolated O_2 lines with an evaluated temperature of T = 419 K and O_2/N_2 = 16.6% by mole. As we move closer to the surface, the relative intensity of the O_2 lines in the spectrum diminishes and the temperature rises. At z = 100 μm, the temperature reaches T = 831 K, with a reduced, but significant O_2/N_2 of 7.9%. Sample single-shot spatial profiles are shown in Figure 13. At the top of the Figure, the temperature is nearly constant near $T \sim 950-1000$ K, with very low O_2 content at, or near, the detection limit of our measurements—a situation in which mixed products of combustion or other fiber/char oxidation are coating the near-surface layer. Below, in the middle portion of Figure 11, the temperature is rising as oxygen is consumed, this profile, which is strongly suggestive of low-temperature oxidative reactions is additionally reflected in the mean spatial profiles, obtained by averaging 400 single-laser-shot results, and displayed at the bottom of Figure 13.

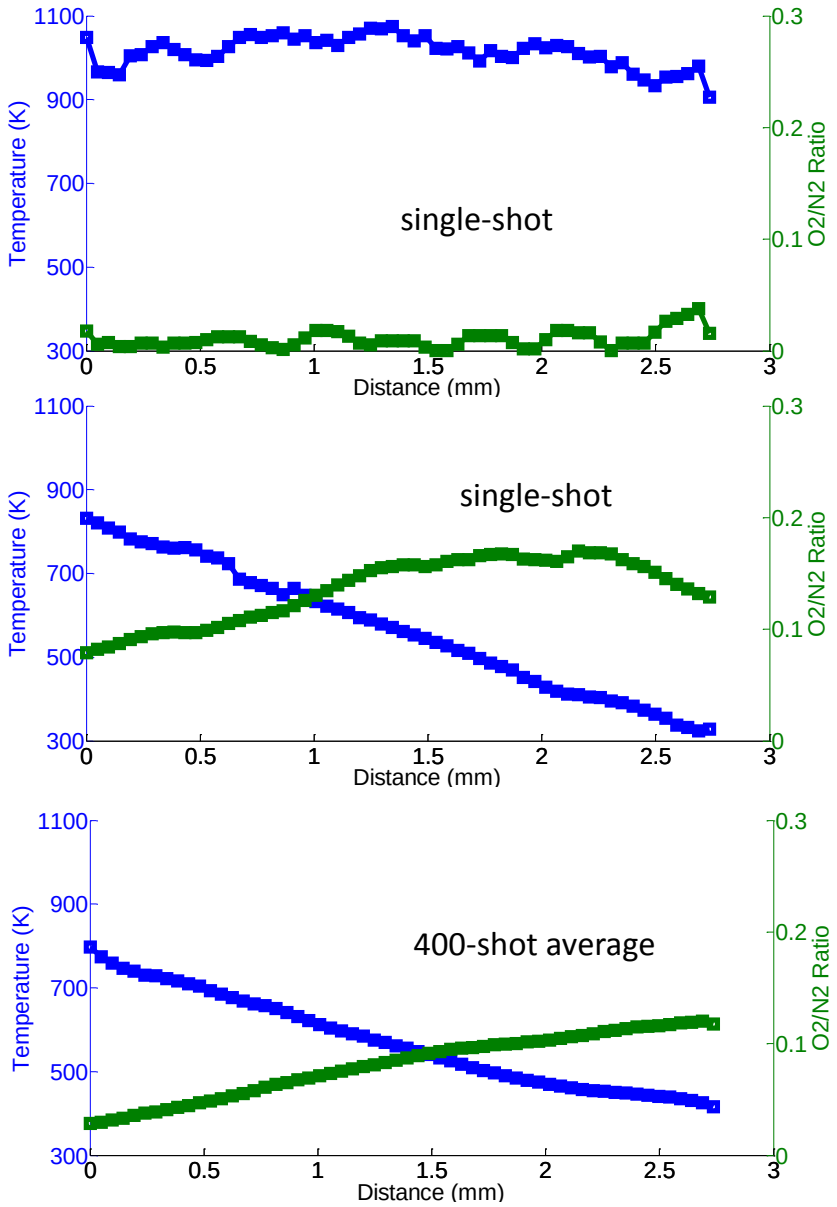

Figure 11. Surface-normal profiles of temperature and O_2/N_2 mole-fraction ratio obtained in the near-surface region of a carbon-epoxy composite material under a heat flux of $q'' = 48.5$ kW/m^2. The profiles were obtained by 1-D CARS imaging during the steady state phase of the experiment.

SUMMARY AND CONCLUSION

We have performed joint temperature/oxygen measurements near the surface of a carbon-epoxy composite material (HEXEL 3501-6) under uniform radiative fluxes in excess of 40 kW/m^2 in a well-controlled experimental configuration. The 100-mm × 150-mm samples exhibited autoignition that was immediately followed by a heavily sooting combustion phase where the vast majority of the epoxy binder was quickly burned away. The sooting phase was followed by intermittent pockets of sooting flames and then a long-duration steady state condition where a both blue and yellow/orange emission were observed to meander over the sample surface. Post-mortem observation of the samples indicated significant consumption of the carbon fiber material from oxidative processes in the steady state portion of the experiment. Pure-rotational CARS was utilized for single-laser-shot measurements of temperature and O_2/N_2 mole-fraction ratio. Point measurements at 1-kHz data were performed in the later portions of the heavily sooting phase and throughout the steady state portion of the experiment, where 1-D spatial profiles were estimated by translating the sample/heater assembly during the burn. These point-measurement data provided several hundred thousand joint temperature/oxygen measurements and two distinct temperature/oxygen characteristics were observed as the sample shifted from sooting combustion of the binder to what appears to be a low-temperature oxidation of the carbon fibers and/or any char material. A second CARS instrument was successfully utilized to monitor 1-D spatial profiles on a single-laser-shot basis, revealing the spatially correlated structure of the near-surface layer. Additional data have been acquired with both CARS instruments at heat fluxes ranging from 32 to 90 kW/m^2 and are available for future analysis.

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