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SELECTED DIAGNOSTICS FOR MICROGRAVITY COMBUSTION SCIENCE

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Introduction

The evolution of our understanding of combustion phenomena occurring under reduced gravity conditions poses a continuing demand for diagnostic tools of increased sophistication. Existing methods have become insufficient to keep pace with emerging refinements in the underlying theories and predictive models. The coupling of physical mechanisms inherent in combustion systems mandates the simultaneous determination of numerous thermophysical quantities, principally temperature, velocity, and species concentrations. Observed differences attributable to variations in experimental configuration, fuels and diluents, and initial conditions enhance the difficulty of developing diagnostic methods suitable for the acquisition of the required data over the desired range of experimental parameters.

Efforts to provide for ongoing diagnostic development supporting microgravity combustion science experiments are conducted within the Microgravity Science Division at the NASA-Lewis Research Center. The following describes recent results from several diagnostic development efforts conducted under this project.

Laser Doppler Velocimetry

Laser doppler velocimetry (LDV) utilizes the frequency shift of scattered radiation to perform remote, non-intrusive measurements of local fluid velocities. Recent advances in both solid-state laser and detector technologies and high speed digital signal processing (DSP) architectures have permitted the construction of compact, mechanically robust systems suitable for microgravity combustion science applications.

The systems described here utilize dual-beam heterodyne detection. This configuration affords optimal performance under the broadest range of measurement applications. The intersection of the dual input beams defines the optical sample volume, which for the present systems is on the order of 70 microns ($1/e^2$ diameter). The doppler shift of light scattered from small seed particles introduced into the flow field is utilized to determine the Eulerian velocity within the sample volume. The capacity for high temporal data rates provides a valuable tool for the investigation of time dependent flows and turbulent phenomena.

Two basic optical configurations are employed, depending on the specifics of the application. A forward scattering system is utilized for applications involving large spectral bandwidths, such as highly turbulent flows. Strongly enhanced forward scattering cross sections permit the use of smaller seed particles in conjunction with relatively low power laser sources. The smaller particles are necessary to follow detailed features of the flow structure with suitable fidelity. The system reported here utilizes a 14 milliwatt diode-pumped, doubled Nd:YAG laser operating at 532 nanometers. Shorter wavelengths are generally advantageous by virtue of the k^4 dependence of the scattered signal. Further compaction of the receiving optics module is achieved via fiber optic coupling of the photodetector. The detector is composed of a low-noise avalanche photodiode (APD) with an integrated preamp and line driver. The use of APD's is favored in this application, since the high quantum efficiency dominates the excess gain provided by conventional photomultiplier tubes.

Optical systems have also been constructed in a coaxial backscatter configuration using laser diode sources emitting at 680 and 780 nanometers. In addition to simplifying alignment considerations, this configuration also provides single-ended optical access. Such an arrangement affords the possibility of rapid spatial scanning of the sample volume using computer controlled turning mirrors or diffractive optics. A system of this type has been constructed for use in the various reduced-gravity facilities. The onboard computer system generates the waveforms to achieve the desired spatial scan sequence, and simultaneously provides timing flags to synchronize with the data acquisition system.

Data is acquired and processed using a novel burst-spectral signal processor. This processor utilizes parallel DSP to achieve acquisition, processing, archiving, and real-time graphic display at rates approaching 10^4 measurements per second. The 16-bit PC plug-in card configuration facilitates integration into a variety of experimental packages. Of particular value in the context of the reduced gravity facilities is the ability to operate the processor as a transient recorder. In this fashion, the original data stream is preserved, allowing flexibility in post-processing options.

Shown in figure 1 is velocity vs. time data corresponding to non-reacting flow from a burner with Re 2100 at the exit. Turbulence is generated by impingement on a diffuser plate located 20 mm upstream of the exit. Also shown is the associated velocity probability density function (pdf). Figure 2 illustrates the mean velocity and RMS of the pdf as a function of axial height above the burner. This data was acquired on the NASA DC-9 reduced gravity aircraft using the forward scatter optical system previously described.

Particle Image Velocimetry

Measurement of velocity maps for flows by using Particle Imaging Velocimetry requires an intense light source manipulated

to form a light sheet which is an illuminated volume with a thickness of approximately 1 mm, a width of at least 50 mm and an axial extent of at least 150 mm. In 1G labs, high-energy lasers are routinely used for this purpose. Use of such a laser in the 2.2 second drop tower is more difficult since the laser head and power supply are too massive to be included internal to the drop package. Therefore, a multi-mode fiber optic cable with a core diameter of 600 micrometers was used to transmit light from the laser to the drop rig. Once on the rig, cylindrical optics were used to suitably condition the light sheet and center it over the burner exit.

Scattering particles were entrained in the fuel flow by placing them in an input plenum through which the gas flowed. The 0.1 mm diameter of the entrance orifice was designed to produce a Reynolds number of 2100 in the plenum when the mean velocity from a 0.312 cm diameter nozzle at the exit of the plenum was 8.72 cm/sec. In initial tests, the seed exited the nozzle in a continuous stream that was much too dense to resolve individual particle images as required. When a screen was placed inside the plenum over the base of the exit nozzle, the particulate stream was disrupted and individual particles could be resolved. The flow velocity was also reduced to a level where the Reynolds number in the plenum was approximately 370. A velocity field map is shown in figure 3. In this illustration, the nozzle is denoted by a square and the OG flamefront location corresponds to the hemispherical line. The axes are labeled according to pixel number.

The same seeder concept was also applied to seeding a 1G flow from a 33 mm ID tube with a non-combusting flow. In this experiment air exited a 33 mm diameter, 600 mm long tube with a mean velocity of 5.23 mm/sec. Given the large tube diameter, a Reynolds number of 1153 was produced with an entrance diameter of 0.3 mm. The flow field is shown in figure 4 where the labels for the axes correspond to distance in inches. In all cases, quantitative velocity maps were obtained from the original raw particle image sequences using analysis tools developed at the NASA-Lewis Research Center.

Simultaneous Soot Volume Fraction and Temperature Measurements

A variety of non-intrusive optical methods have been demonstrated for the determination of soot volume and fraction and temperature. Specifically, optical extinction has been utilized for the former, and emission pyrometry for the latter. Both examples involve the tomographic inversion of integrated line-of-sight data. Recently, a method was developed to permit the rapid, two-dimensional determination of soot volume fraction fields. A system has also been developed for the Combustion Module-1 program to determine soot temperature fields via two-wavelength emission tomography.

The present effort focuses on performing simultaneous measurements of volume fraction and temperature, while also addressing issues concerning the specification of the spectrally dependent emissivity for carbonaceous soot. This work is an extension of previous efforts by Hall and Bonczyk, essentially extending the method to multi-dimensional measurements. The method is predicated on the fact that [in the optically thin limit] Kirchoff's Law establishes the equivalence between absorptivity and emissivity. Since optical extinction in effect determines per volume absorptivity, emission measurements performed along identical optical lines of sight yield path integrated data proportional to the associated extinction values. The constant of proportionality is the Planck Function, leading directly to the determination of temperature without the need to explicitly determine appropriate values for soot emissivity.

To insure this proportional equality, it is essential that the emission and extinction measurements be specified over identical optical paths. Isotropic emissions must therefore be collected over narrow, spatially non-overlapping ray fans. When utilizing a pixel-based detector array, the permissible collection angle is determined by the quantity $d_p/2r_iM$, where d_p is the dimension of a pixel, r_i is the maximum radius of the emitting species, and M is the system magnification. Achieving a spatially invariant angular collection efficiency is accomplished through the use of a telecentric imaging system.

Line profiles from a resulting SVF and temperature map are shown in figure 5 for the case of a 3.85 cc/sec ethylene-air coflow burner. Data from previous measurements by Santoro et al are shown for comparison. As would be expected, temperature measurements derived from concomitant SVF measurements yield unphysical values in regions where the soot loading becomes negligible. This is consistent with the concept of measuring the temperature of the soot field itself. In the laminar diffusion flame, the location of the soot shell occurs at radii internal to the reaction surface, and therefore measurements of soot temperature obtained by this method would not be anticipated to accurately determine peak gas phase temperatures. Figure 6 depicts similar measurements in a Re 2550 turbulent acetylene diffusion flame. Due to significantly enhanced mixing, the occurrence of soot is less sharply confined, as observed in the preceding laminar flame data.

Rapid-Insertion Fine Wire Thermocouples

The use of rapid-insertion fine wire thermocouples provides a simple complement to emission pyrometry techniques. The latter, when implemented in the visible spectrum, are dominated by radiant contributions from soot. While isolated gas phase emissions are observed in the infrared, the output still remains a line-of-sight integrated quantity. This measurement therefore provides a useful complement for the determination of spatially localized temperature measurements in possibly non-sooting regions of combustion phenomena of arbitrary symmetry.

Minimizing the intrusive nature of a physical probe is enhanced by reductions in thermal mass, aerodynamic cross section, and residence time. The importance of these features have been confirmed by high speed imagery and high speed schlieren

photography of thermophoretic soot sampling probes. To this end, an identical pneumatic actuator assembly was used for the present thermocouple measurements. In this case, the 2 mm gap in the tip of the probe normally occupied by the transmission electron microscopy collection grid is spanned by a fine wire thermocouple. The results reported here were obtained using type K thermocouples with a wire diameter of 1 mil. The active junctions were formed by laser welding, forming a spherical bead of approximately twice the wire diameter. The raw leads are bonded to the surface of the probe blade with a thin, high temperature, electrically insulating coating.

To reduce conductive effects along the metallic leads, the thermocouple was oriented perpendicular to the blade gap, and along vertical axis of the flame. The exposed thermocouple leads are therefore exposed to minimal thermal gradients. The use of 1 mil wire places the bead 40 wire diameters away from the larger thermal mass presented by the probe blade. The apparatus is oriented so that the thermocouple bead falls on the centerline of the burner axis when the actuator is in the fully extended position.

Typical raw voltage response functions are shown in figure 7 for the case of a turbulent acetylene jet diffusion flame at Re 2550. Convective and radiative corrections have not yet been applied. The junctions were located 100 exit diameters downstream. The actual residence times of the probe were measured with a simple optical gate. The gate is formed by a laser sheet which is interrupted by the traversing probe. Following the probe, the sheet is focused onto a high-speed PIN diode, and stored on a digital sampling oscilloscope. Shot-to-shot variations in residence time are negligible. Extrapolations based on an exponential response model demonstrate good agreement between sequential measurements. The observed slight monotonic increase in response time from sequential insertions is attributed to the increase in bead diameter due to the deposition of soot.

Miniature Spectrometer Detection of Visible Flame Emissions

An important observable in microgravity flames is the color of the flame, or more specifically, the spectral distribution of the flame emissions. This may lead to conclusions about the types of species present in different flame regions, comparisons of the relative amounts of the species between microgravity and normal gravity flames, and to the results from flame models. On a practical level, the intensity distribution may guide the selection of optical bandpass filters and light sources for imaging measurements. Conventional laboratory monochromators offer high resolution, but are large and sensitive to mechanical shock. A solid-state, miniature spectrometer, the MMS 1, has been obtained from Carl Zeiss, GmbH to address this specific need.

The entire unit is 70 mm x 60 mm x 43 mm, features a glass body spectrometer, and contains an integrated grating and linear diode array. An input optical fiber bundle composed of approximately 30 single fibers couples the input to the spectrometer, and has an inner diameter of 0.5 mm. It converts the light from a circular input to a linear output of 70 micron by 2.5 mm that forms the input slit of the spectrometer. The grating is holographically blazed to have its maximum efficiency at 215 nm, and images the entrance slit onto the diode array. The same grating is used throughout the uv and visible. The spectrometer has a 256 pixel element linear diode array that simultaneously records a complete spectrum over the range of 300 to 1150 nm.

The electronics are in a separate module that interfaces between the spectrometer and the computer. An analog/digital card in the PC104 computer (described later in this paper) on the drop rig triggers data acquisition and digitizes the signal from the electronics module. A Pascal computer program controls the experiment sequence, including activation of a gas solenoid, hot wire ignitor, and data acquisition.

Prior to use in the drop tower, the MMS underwent a series of laboratory tests. Three sources were used to check the wavelength calibration: a small mercury pen lamp, a helium-neon laser, and a nitrogen laser. Each separately illuminated the fiber optic input to the spectrometer. The peaks were fit to a Gaussian to determine the pixel positions of maximum intensity. Using calibration coefficients supplied by the manufacturer, agreement of the main mercury lines at 365, 404, 435, 545, and 578 nm, and the laser lines at 632 and 337 nm to the measured wavelengths was obtained for five of the lines to within 0.3 nm, agreeing with the manufacturer's specification.

The relative spectral response calibration was done using a quartz-halogen tungsten coiled filament lamp. The system response is not flat, but exhibits a peak sensitivity at 600 nm, falling to 10% of the peak at 415 and 920 nm. The lack of response below 415 nm is due to the optical elements in the lens. A correction function was generated and applied to the subsequent flame spectra to account for the spectral response of the lens/detector system. Above 920 nm, most of the large fluctuations seen in the spectra may be attributed to the smaller detector response. The spectrometer linearity with integration time, from the minimum time of 10.5 msec up to 100 msec, was examined using an atomic spectral lamp. Linearity for different line intensities was observed up to near the bit count limit of 4095.

An initial test drop was conducted using a set of light emitting diodes in the green, red, and near infrared. A comparison of the wavelength maxima location and intensities before and during the drop shows slight changes on the order of 0.5 nm and 3% decrease in intensity.

For a demonstration of flame spectra, the MMS is mounted onto the optics plate of a 2.2 sec drop rig. A 50 mm F/2 macro lens collects the flame emissions and focuses them onto the fiber optic. The magnification is roughly 1/3, so that only a small part of the flame is imaged onto the input diameter of the fiber. A pinhole is used at a separate time to measure the position in the flame that the spectrometer views. Typical accelerations at the end of the drop are between 10-20 G as measured by a

shock accelerometer mounted near the spectrometer. A simple laminar ethylene diffusion flame was chosen as it is commonly studied and easily and reliably ignited. The nozzle inner diameter of 2.5 mm and ethylene flow rate of 0.072 sccm gives a flame 2.2 cm high. The operational sequence is collection of a background (dark) spectrum, flame ignition in 1-g by a hot wire, collection of several 1g spectra, release of the drop package, and collection of transition and 0g spectra. Video is taken of the flame during the entire sequence.

The first set of drops was conducted with the spectrometer imaging low in the flame, 5-7 mm above the nozzle. The flame has a blue color to the eye at this height. The integration time is 33 msec to obtain satisfactory signal levels. The transition to a stable 0G flame appears to take about 1 second, after which the flame spectra are nearly identical until the end of the drop. The spectra in 1G and 0G look qualitatively similar except for the magnitudes, as shown in Figure 8, and show a continuous emission as would be expected from a spectra dominated by particulate emission. Surprisingly little emission or structure is seen in the blue wavelengths above 415 nm that can be detected by the optical system. (The spectrum from a butane flame shows prominent CH emission at 431 nm and C₂ emissions at 473 and 516 nm.) The peak emission occurs in both 1G and 0G flames in the near-infrared, near 950 to 1000 nm. In general, the 0-g spectra are weaker by 2 to 5 times those in 1-g with the greatest 1-g/0-g ratio occurring at 450 nm. The greatest subtracted difference occurs at 900 nm.

Higher in the flame near the center, at 9-10 mm above the nozzle, the signals are considerably stronger. The flame has a yellow color to the eye at this height. The integration time is reduced to 15 msec to keep the signals from going off-scale. The peak wavelength in 1G is 975 nm; in 0G, the peak is not reached, as the signal is still increasing with wavelength. The differences between the magnitudes of the 1G and 0G spectra are even more dramatic than those lower in the flame as shown in Figure 8, with the 1-g/0-g ratio being over 50 times at 525 nm. The greatest subtracted difference occurs at 950 nm, similar to lower in the flame.

One preliminary test of a 1G methane diffusion flame showed that it is considerably weaker than the ethylene flame and blue-shifted in its emissions, as expected from its appearance to the eye. An integration time of 100 msec yielded signals that are roughly 50 counts, compared to over 3000 for the ethylene flame with an integration time of only 15 msec.

To date, the MMS has been subjected to 42 drops. The above results show that this spectrometer system is able to spectrally resolve flames and provide information on their radiant emissions in the visible. A uv-vis version of the MMS was recently received and will be tested for its applicability to enhance the blue and ultraviolet emissions from species such as OH.

Data Acquisition and Control for Microgravity Diagnostic Systems

Advances in diagnostic techniques utilized in the reduced gravity facilities have resulted in the requirement to upgrade the associated data acquisition and control capabilities. A PC104 system was selected for several reasons. First, it is a primary standard for embedded systems. This standard provides a platform that is virtually identical to the desk top PC; the system configuration is based on the standard 16 bit ISA bus. Numerous vendors manufacture boards that will readily mate with this bus architecture. This provides ready availability of a broad variety of capabilities, including power supply cards, CPU cards, frame grabbers, analog signal conditioning, digital I/O, etc. Another important factor is size. Basic cards have an outline of less than 100 by 100 mm. When stacked, the cards are separated by 15 mm. The minimum system can therefore be packaged into a 150 x 150 x 50 mm. An additional motivation is consistency with laboratory applications. Most bench top systems can be duplicated in the PC104 format. Programs written to run under DOS will also run with out modification on a PC104 system.

The present configuration consists of a 486 CPU, a PCMCIA interface, and a data acquisition card. The data acquisition card has 16 single ended or 8 differential analog inputs, digitized to 12 bit resolution with a maximum sampling rate of 200 kilohertz. Analog outputs are supplied through two 12 bit D/A converters. Also provided are 16 digital lines which drive the various solenoids, relays, and status indicators. As configured the system requires only a 5 volt input, and typically consumes 6 watts of power. Should the need arise to alter this configuration, a second acquisition card can be added to the stack to enhance or expand these capabilities.

Upon initialization, the system loads DOS from the solid-state disk (SSD) on the CPU card. The config.sys file and autoexec.bat files in the SSD load all of the necessary system drivers. The final command in the autoexec.bat runs a batch file on the PCMCIA flash card. The data acquisition program can then be executed from the PCMCIA card. Data taken during the experiment sequence is then stored back to the same card. Upon completion, the card is removed, and interfaced to either a laptop or desk top machine to analyze and archive the data. In this fashion, the data acquisition program can be changed without having to gain access to the system, facilitating parallel utilization by several users.

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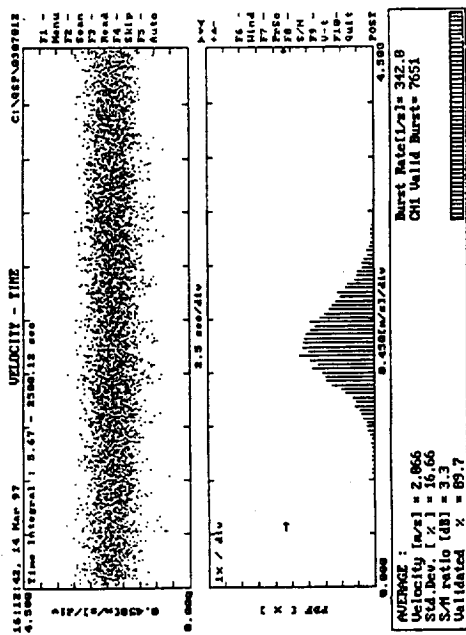


Figure 1: Velocity vs. time and pdf for turbulent non-reacting jet in 0g

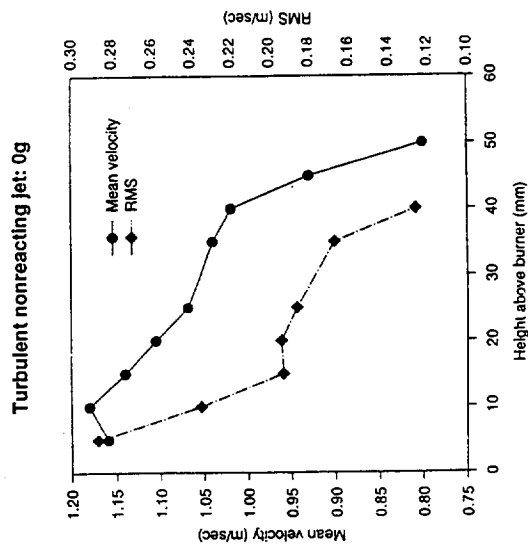


Figure 2: Mean velocity and RMS vs. height above burner for turbulent non-reacting jet in 0g

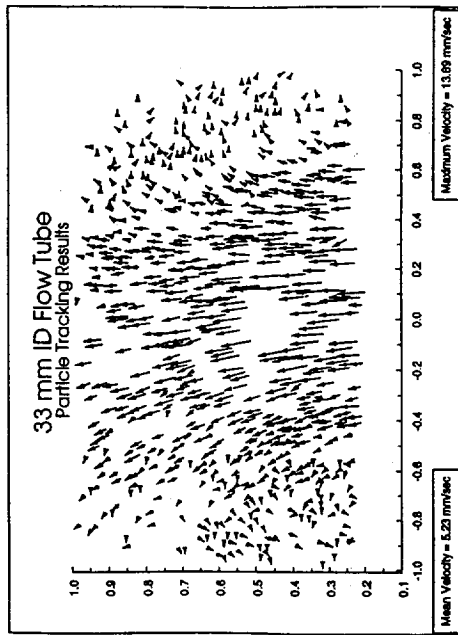


Figure 3: Velocity map for low velocity non-reacting jet in normal gravity

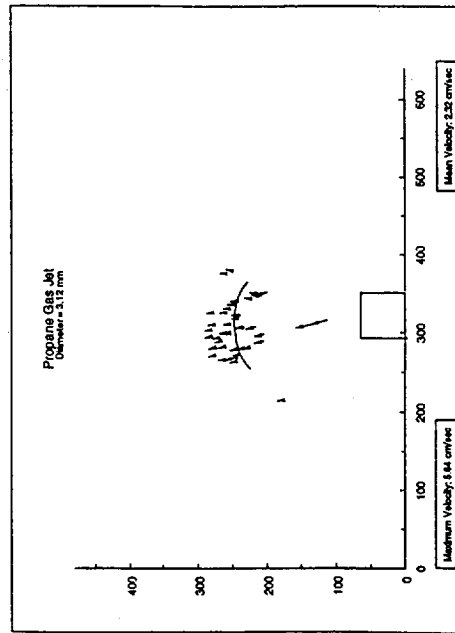


Figure 4: Velocity map for propane jet diffusion flame in 0g

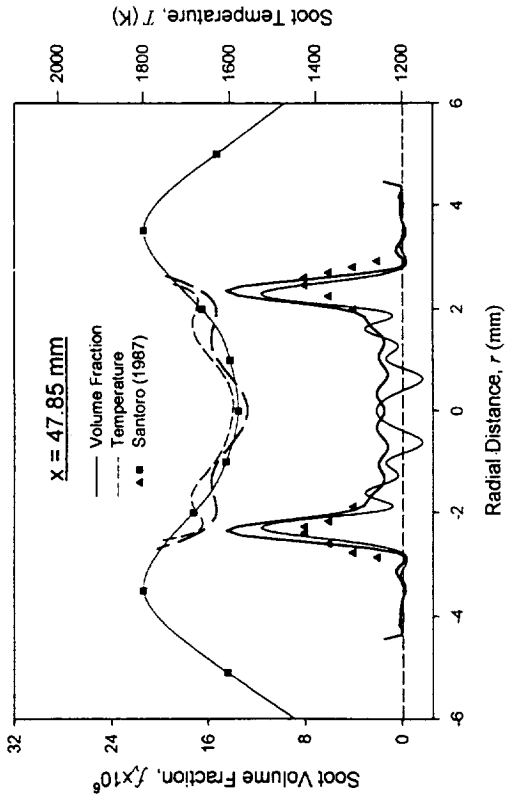


Figure 5: Soot volume fraction and temperature for 3.85 cc/sec laminar ethylene diffusion flame

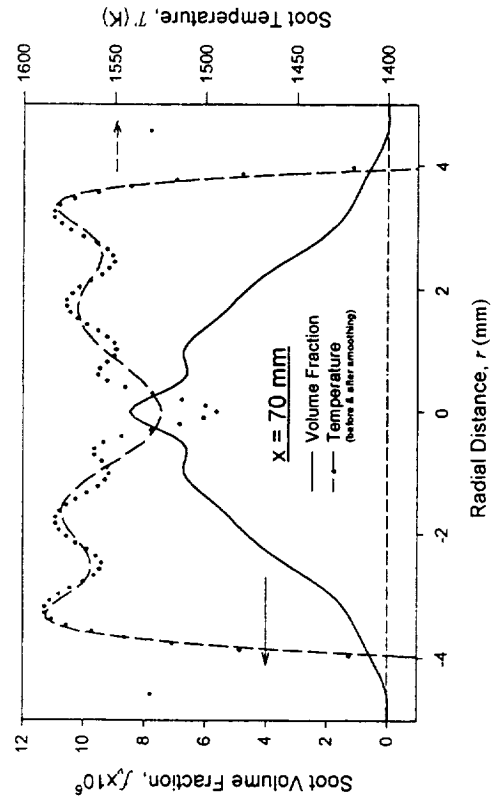


Figure 6: Soot volume fraction and temperature for Re 2550 turbulent jet acetylene flame

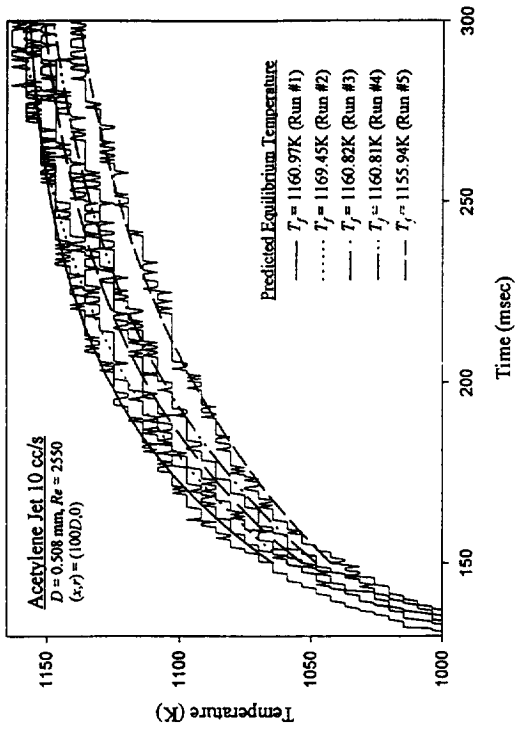


Figure 7: Transient response of 1 mil thermocouples in Re 2550 turbulent jet acetylene flame

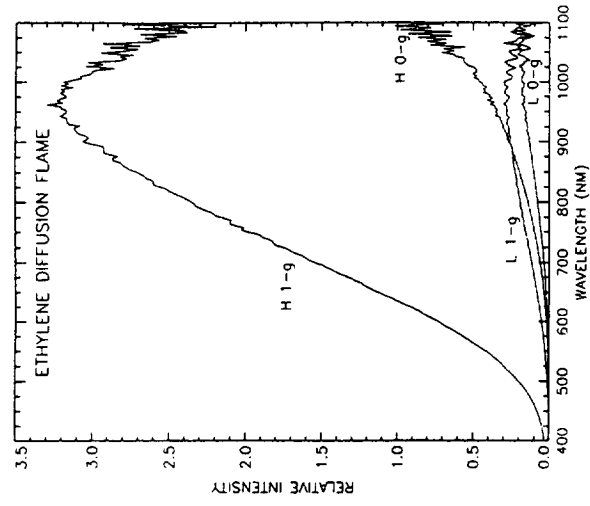


Figure 8: Spectral emission from ethylene jet diffusion flame in normal and reduced gravity
H: 9-10 mm above burner; L: 5-7 mm above burner