# SELECTED MICROGRAVITY COMBUSTION DIAGNOSTIC TECHNIQUES

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Abstract

During FY 1989-1992, several diagnostic techniques for studying microgravity combustion have moved from the laboratory to use in reduced-gravity facilities. This paper discusses current instrumentation for rainbow schlieren deflectometry and thermophoretic sampling of soot from gas jet diffusion flames.

## I. Rainbow Schlieren Deflectometry

Knowledge of the temperature field surrounding a combustion event is typically desired, particularly in microgravity combustion studies, to assess the relative importance of buoyancy. While temperature information may be obtained by intrusive devices such as thermocouples, this can significantly perturb a reduced gravity flame. Therefore, optical methods are preferred, with interferometry the most common approach. Interferometry is not without its drawbacks: temperature must be calculated from refractive index data, which are not always available, optical elements, paths and path lengths must remain fixed to a high degree of accuracy and visualization is difficult. One method of addressing the latter problem is the use of a grey-scale schlieren system, but the eye is relatively insensitive to grey scale differences. By replacing the Schlieren knife-edge with a color bar filter continuously varying in hue and the typical monochromatic source by a white light, gradients in the refractive index field are displayed as colors in the final image[1-2]. Howes has shown[3-4] this technique is as sensitive as Mach-Zehnder interferometry. Greenberg[5] et al, utilize computer generation of filters and processing of the image to obtain accuracies as good as those available with interferometry with the added benefit that requirements on optical path length and element stability are greatly relaxed. While the final information is given in terms of a refractive index, some knowledge of the combustion constituents and products allows calculation of temperature profiles. Due to these advantages, we have pursued development of this technology.

A schlieren optical system featuring off-axis parabolas (OAP's) is detailed in Figure 1. Due to the nature of schlieren optics, the collimating/decollimating mirrors are larger than the field of regard. As the field is increased, the cost of OAP's can rise dramatically. In addition, they present interesting alignment challenges. While the aforementioned difficulties do not necessarily preclude the use of OAP's, we have also pioneered the development of schlieren systems whose collimating mirrors are rotationally symmetric but are tilted with respect to the optical axis passing through the test section.[6] The primary mirrors may have either a spherical or parabolodial figure while catalog lenses correct the tilt-induced aberrations. All lenses have a broadband antireflection coating due to the large number of air/glass interfaces present.

Final complications in the design of these systems relate to the spatial and spectral properties of the fiber-optically coupled arc lamp that is used as a light source. With the sensitivity of a Rainbow Schlieren device proportional to the focal length, our systems had a F number as high as 30; most fibers emit light into an F-cone of roughly 2.5. Therefore, in one of our systems we place the fiber at the front working distance of a well-corrected microscope objective, which converts the F number to approximately 20, conserving sufficient throughput for the system to function properly.

Quantitative color hue measurements require a rugged source that is spectrally stable with time and has a uniform spectral intensity. We use a fiber-optically coupled arc lamp from ILC Technology. In this device, a feedback-stabilized xenon arc placed at one focus of an ellipse is coupled into a cylindrical sapphire waveguide at the other focus. The output end of the waveguide is polished to a radius of curvature that produces a focus with a numerical aperture that matches most fibers, although the spot produced is less than optimal. This lamp has the unwanted property of generating large amounts of infrared radiation relative to the amount of visible light, which mandates attention be given to thermal loading in the arc lamp housing. We have experienced failure of the fiber coupler on one of our experimental rigs due to extreme heat loads.

Hue stability of the source is directly related to calibration requirements of the instrument. Since we interpret hue shifts as a ray deviation from a refractive index gradient, a change in the color output with time increases the amount of deviation required to observe a change in hue greater than the RMS noise. Our source tends to exhibit long-term drift over a period of approximately four hours. Therefore, any calibration older than roughly four hours exhibits somewhat decreased accuracy.

The concept of calibration ties together two issues: filter linearity in hue shift and filter fabrication. In the optimal case, a change in position of a ray striking the filter relates linearly to a change in hue as interpreted by the optical system. We represent color via utilization of the tri-stimulus values of red, green and blue in a Hue Saturation Intensity (HSI) model. Throughout its range, the filter changes hue continuously while remaining fully saturated. In fabricating a filter, we begin at one edge with red and progress around the HSI cone, while remaining at a constant intensity and saturation level. Due to the circular nature of the model, colors on the extreme ends of the filter are the same. When the hue has completed a full cycle, saturation is gradually reduced until all three colors contribute an equal amount producing a white band which appears on both ends of the filter. We use two methods to produce a filter. The pattern may be photographed on 35 mm slide film from the display of a high-resolution computer monitor. When taken as a single exposure, the background is black, which acts as a low-pass filter, reducing resolution in the final image. A double exposure which creates a clear background eliminates that problem. Alternatively, we can create digital set of values to describe the filter and from this set, a computer group at Lewis can produce slides.

The preceding discussion deals only with the fabrication of a filter in an ideal system. When such a filter is placed in an actual device with an empty test section, the non-uniform film sensitivity combined with uneven source and instrumental spectral transmission profiles result in a nonlinear variation of hue. To correct this problem, the filter is placed in the actual system and a spot is scanned across the filter and the hue recorded as a function of position. Our custom software then transforms the prescription for the original filter to one that, while irregular in an absolute sense, creates a linear hue variation when used in that specific system. An added complication is that the light source varies spectrally over the period of a few hours and exhibits long-term drift. While this reduces the accuracy of the measurements, we resolve gradients to roughly 0.2%. Given other uncertainties in the system, errors produced from source drift are rarely the limiting factor. However, new filters can and should be fabricated at regular intervals of lamp usage and when the lamp is replaced.

The final image of a rainbow schlieren system may be stored on video tape for later viewing and also as a data source for programs which invert the data and produce a quantitative refractive index field. We do not find the noise floor of the video system to be the limiting factor in the accuracy of the data. Video tape decreases the spatial resolution available, but does not have a large effect on the signal-to-noise ratio. We also observe that the CCD camera and transmitter generate no measurable increase in the noise floor.

In the use of a rainbow schlieren system, the size of the filter must be chosen to match the expected ray deflections. As the magnitude of the refractive index gradient grows, the ray displacement in the filter plane increases as well. Typically, we measure angular deviations on the order of two milliradians, which determine the size of the filter. While some researchers request angular deviations as large as eleven degrees, this is generally not a realistic number for a rainbow schlieren system for two reasons. First, filter size, generation and mounting become difficult, if not impossible. Second, the accuracy of the measurements can be severely degraded due to the presence of coma in the system. Rays parallel to the optical axis suffer only from spherical aberration, while those propagating at some angle with respect to the optic axis are generally affected by other aberrations, the magnitude of which varies with the correction included in the optical design and fabrication tolerances. As coma is introduced, accuracy suffers because coma may be thought of as a variation of focal length across the field. Since knowledge of the focal length is required to calculate the refractive index distribution, the effects of coma must be considered.

Finally, we use filters somewhat larger than that required by the predicted ray deviations. As rays approach the edge of the filter, care must be taken to avoid interpreting the cutoff region as data. To avoid this problem, we reject any data close to the edge.

## II. Soot Diagnostics

Diagnostic efforts in the study of soot have been directed toward determining size distribution and number density of soot within gas jet diffusion flames. To this end, we have demonstrated thermophoretic sampling in both 0 and 1 G laboratories and have performed imaging light extinction in 1 G.

Thermophoretic sampling is well established as a useful method for studying soot[7-11] in numerous types of flames. This technique consists of inserting Transmission Electron Microscopy (TEM) grids in the sooting region of a flame long enough to allow no more than ten percent of the surface to be covered with soot. TEM Photos of the aggregates are then digitized and computer processed to determine primary size distribution and aggregate dimensions. We implement this technique in a rig utilized in the 2.2 second drop tower at the NASA Lewis Research Center.

A simulated microgravity diffusion flame is illustrated in Figure 2 with a flow directed axially along the burner. In the region above and to the side of the flame, two thin stainless steel probes are shown, both of which support carbon-coated TEM grids. As implemented in our rig, the probes are thermally isolated from the flame using a thin aluminum plate with a slit oriented along the axis of the burner, with the probes attached to a pneumatically-activated support. The burner nozzle, probe support structure, and accompanying electrical and gas delivery systems are located in the combustion chamber at one end of the diagnostics rig (shown as Figure 3 in reference 12.) During a typical drop test, electronics within the rig sense the release of the package into free-fall and immediately ignite the flame. Approximately 1.4 seconds after ignition, the thermophoretic probes enter the soot shell and remain for roughly 40 milliseconds. We have found this is long enough to collect a sufficient amount of soot without violating the ten percent criterion.[10-11]

Following the drop, probes are removed from the rig and the grids photographed using the TEM. These negatives are then backlit and the image digitized using commercial CCD arrays and frame-grabber boards. A mix of in-house and commercial software allows us to measure primary size distribution as a function of height, radial position in the flame and maximum aggregate length. In addition, an intensity histogram, when correlated with the grey-scale background cutoff, gives the number of soot pixels in the two-dimensional image. This in turn yields the total 2-D projected area of the 3-D aggregate through use of an approximation.[10,11,13] We have found the size of primaries to be approximately a factor of two larger in low gravity and the aggregates as much as twenty times longer. While the approximation is thought to hold for aggregates of 2500 primaries or less, Köylü and Faeth[11] use it for slightly larger agglomerates. Due to the large size of our aggregates, we are also forced to extrapolate beyond the assumed limit. To date, we have measured only one aggregate with more primaries than the largest of Köylü and Faeth. We intend to examine the model[13] of Meakin, et al. in greater detail to adapt it to our larger aggregates.

A graph plotting the log of the estimated number of total particles versus the log of the maximum aggregate length divided by the average particle diameter, similar to those from References 10 and 11 is shown in Figure 3. The soot is sampled 10 mm above and 8 mm radially from the nozzle of an ethylene diffusion flame with a burner diameter of 2.29 mm and a flow rate of 1 cc/sec. While current data is somewhat sparse as of this writing, fractal numbers are $1.46 \pm 0.12$ for normal gravity and $1.93 \pm 0.16$ for reduced gravity, indicating the possibility of different aggregation processes.

The foregoing analysis produces a reasonable indication of soot size distributions within the flame. On the other hand, thermophoretic sampling does not yield information about the total quantity of soot present in the flame. Therefore, the drop tower rig is also configured for imaging absorption, shown schematically in Figure 4. Light from a He-Ne laser is spatially filtered, expanded and collimated, following which it passes through the test section. As this light encounters the soot shell, it is absorbed or scattered. By making grey scale measurements of the background before the test and comparing those values to the reduced values seen while the flame is burning, quantitative data are obtained describing the total amount of soot present. We implement this procedure in our laboratory and have begun the process of incorporating it into the aforementioned rig used in the 2.2 second drop tower. The largest problem to date is a shifting of the spatial filter and/or laser beam when the package is released into freefall. A hardened spatial filter assembly is now in place and renewed tests should begin shortly.

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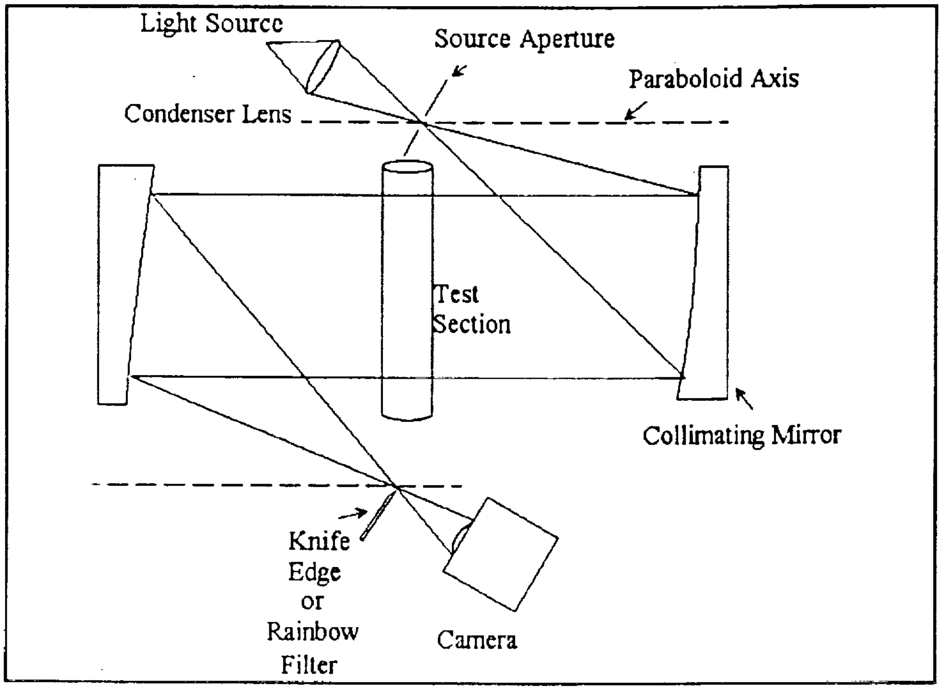


Figure 1
Typical Schlieren Optical System

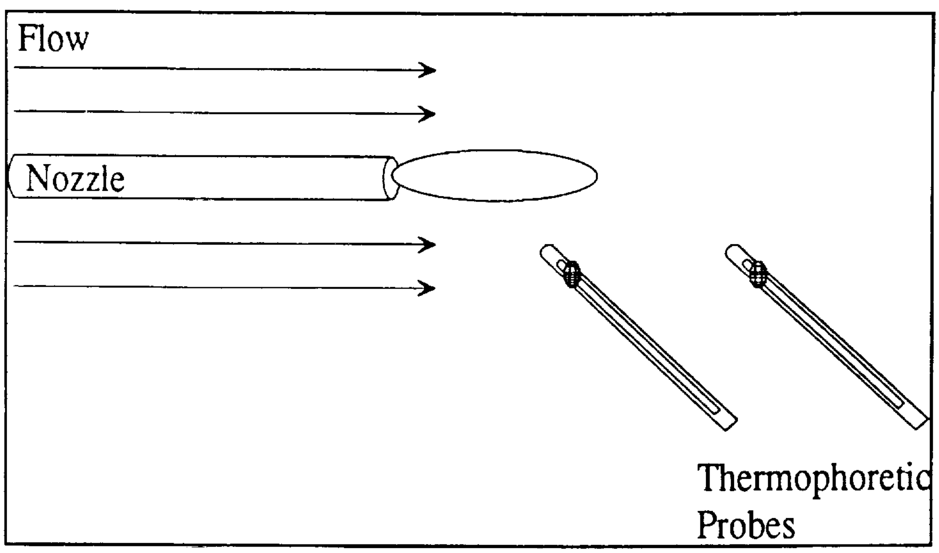


Figure 2
Thermophoretic Soot Sampling Geometry

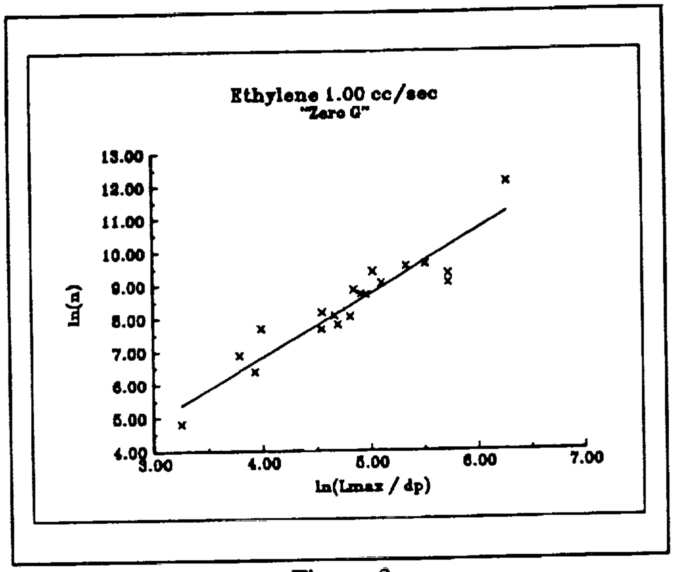


Figure 3
Analysis of Ethylene Aggregates

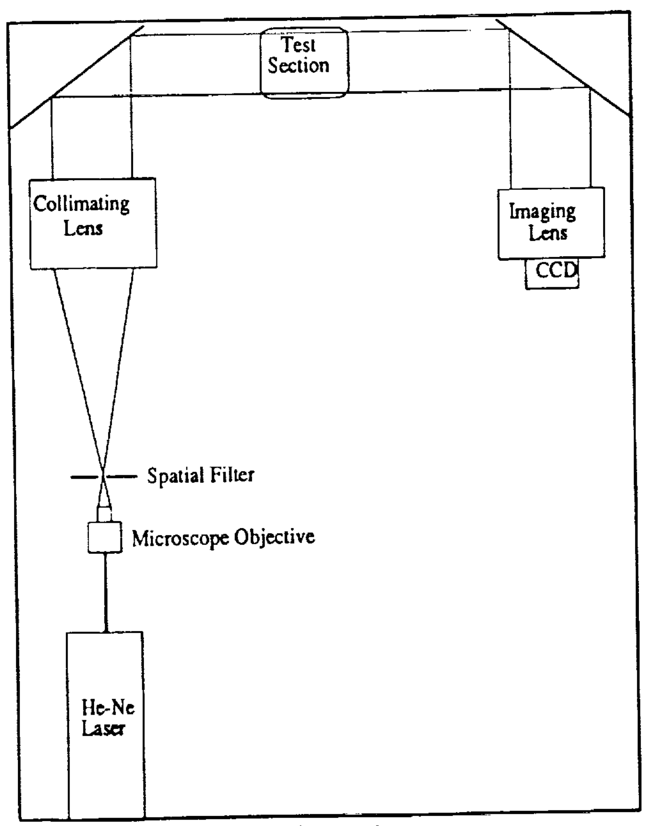


Figure 4
Imaging Absorption Geometry

## COMMENTS

Question (Dr. Michael Winter, UTRC): What degree of temperature accuracy is available in the liquid- and gas-phase measurement using the rainbow schlieren technique?

Answer: Accuracy in using the rainbow schlieren technique for either gas or liquid phase temperature measurements depends on several quantities. First, the path length in which the refractive index changes must be known to a high degree of accuracy. This is much easier to determine for liquids with fixed boundaries or general axisymmetric distributions. In addition, the sensitivity of the system increases with the focal length of the decollimating lens. Finally, the quantity calculated is not temperature, but the refractive index distribution. Therefore, knowledge of the constituent substances and the dependence of their index on temperature is required before an accurate determination of the temperature can be made.

The foregoing begs the initial question (i.e., what temperature accuracies are available). We have measured liquid-phase temperatures with a full-field difference of 1 K and a resolution within that field of 0.2 K. While we have reconstructed refractive index profiles for gas-phase distributions, we have not yet performed temperature calculations, but expect to do roughly an order of magnitude worse.

Question (A. Gomez, Yale University): Thermophoretic sampling used to capture aggregates as large as 12 mm may suffer from some biasing with respect to particle size, since you operate in the continuous regimes (Kn approximately $10^{-2}$ to $10^{-1}$). On the other hand in the free-molecular regime (Kn greater than 1), which is typical of n-gravity flames, there is no size-dependent effect on sampling. Could you comment on this complication?

Answer: Thermophoretic sampling of soot is a well-established technique for the study of soot produced in varying flames. [1-3] These studies were performed under normal gravity conditions. This question is directed specifically toward sample biasing due to operation in the continuum regime for large aggregates present in reduced gravity. A recent paper by Rosner, Mackowski and Garcia-Ybarra[4] has shown that even in this extreme, the maximum sampling bias will be at most approximately 20 percent. Therefore, the influence on population samples, morphologies or light scattering properties should be small. Since the fractal number is calculated using the slope of the best-fit line when plotting number vs. normalized size, this quantity should be imperceptibly affected.

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