

QUALITATIVE AND QUANTITATIVE IMAGING IN MICROGRAVITY COMBUSTION

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Introduction

The study of combustion often begins by asking simple questions such as these: Is there a flame? What color is it? What is its spatial extent and structure? What is its reaction rate? Does it vary with time? How long does it persist? How fast does it spread? Asking these types of questions is especially appropriate in microgravity combustion, where the effects of the removal of buoyancy often produce unexpected and dramatic changes. Images of the flame provide the answers to these questions and an overall view of the time and length scales of combustion processes, and guide the application of other diagnostics. In addition, flame imaging is often the easiest non-intrusive diagnostic to implement, especially in microgravity combustion where physical constraints limit the diagnostics able to be used.

This paper provides an overview of the imaging techniques implemented in the laboratory and reduced-gravity facilities by researchers in the in-house and external microgravity combustion program. Examples of each technique demonstrate the variety and extent available. For a more complete description of the experiment and combustion results, the reader is invited to refer to the references and to the other papers in this conference proceedings. Techniques under further development are also mentioned.

Visible and Ultraviolet Imaging

The use of commercial monochrome and color video cameras for imaging in both drop tower and aircraft experiments is routine. Recording of images on S-VHS, Hi-8 mm, 8 mm, or Betacam tape and/or direct digitizing by a frame grabber depends on the specific experimental requirements. A comparison of monochrome signals digitized directly from a camera compared to those digitized from the Betacam recorder shows that the digitized signals at each pixel are identical to 8 bits of resolution, even when the recorder is in digital pause mode. This provides great advantages for users requiring quantitative data at 30 frames per sec for extended lengths of time. During the recent upgrade of the NASA Lewis 2.2 sec drop tower facility, a dual channel, high bandwidth (6 MHz) frequency modulated fiber optic video transceiver system was installed to provide low loss signals especially suited for quantitative imaging such as for rainbow schlieren or laser light extinction. In the future, a color digitizer at the top of the 2.2 sec drop tower with network capabilities to transfer data may be available. In the NASA Lewis Zero Gravity facility, two 8-mm video recorders reside on each drop bus to record images from the users' cameras. Aboard the NASA reduced-gravity aircraft, S-VHS and Hi-8 mm video recorders have been used by many investigators.

In many studies of microgravity combustion phenomena, systems lie near the limits of flammability, ignition, or stability, and typically have a dim flame. The use of intensified array cameras reduces many of the difficulties in imaging these flames. The intensifier acts as a photon amplifier, thereby allowing

the imaging of flames too dim to be detected by film or standard video cameras. The first application of this type of camera to microgravity experiments was in the study of weakly luminous flames spreading across ashless filter paper samples aboard the NASA Learjet (ref. 1). The problem of how to set the camera gain to provide the correct exposure was noted, as many of the images were saturated when the gain was adjusted by observing the monochrome image on a monitor during the experiment. Soon after, an intensified array camera was used in the study of lean, premixed hydrogen flames at low Lewis numbers. The camera could image the flames without any colorant added, as was required for movie film imaging in 2.2 sec drop tower tests. New, unpredicted flame structures and behaviors were observed aboard the NASA KC-135A (ref. 2). This type of camera is scheduled for use in a spaceflight experiment in the spring of 1997 to study the long-term behavior of these flames in microgravity. A wide field of view of 30 cm x 22.5 cm, depth of field of 30 cm, and spatial resolution on the order of several mm are accommodated by a custom lens. The gain of the camera will be set by digitizing the video signal, applying a false color look-up-table, and displaying the false color signal on a monitor. The operator observing the false color signal will adjust the camera gain to insure the image is just below saturation.

In another spaceflight experiment, the study of droplet combustion (ref. 3), plans for spaceflight include the use of an intensified array camera having sensitivity in the ultraviolet. Demonstration of the intensified array camera in the drop facilities yielded OH chemiluminescence images of burning isolated heptane droplets by using a bandpass filter centered at 310 nm. The field of view and depth of field were 4 cm x 4 cm and 3.3 cm, respectively. The camera gain was adjusted so that the profile of the digitized image of the flame was not saturated. Additionally, the experiment used a high speed (80 frames per sec), 35 mm movie film camera to obtain high resolution images of a backlit droplet view. The field of view and depth of field were 3.3 cm x 3.3 cm and 3 cm, respectively. The spatial resolution was 18 microns. The movie film was scanned at a resolution of 5080 dots per inch into a TIFF file. The high resolution enables accurate measurement of droplet extinction diameters as small as 100 microns.

A more sophisticated approach is being taken in a sounding rocket experiment to study influences of radiative heat transfer on flame spread over polymethylmethacrylate (ref. 4). An intensified array camera is equipped with a rotating wheel having six filters: red, green, blue, OH (310 nm), CH (430 nm), and clear. A recording rate of five images per second for each filtered image is achieved by rotating the wheel at 30 Hz in synchronization with the framing rate of the camera. The gain of the intensified camera is fixed for all the frames throughout the experiment, and the exposure time is varied for each filter automatically by the camera operating in a peak mode. The camera response will be calibrated with the filters in place using a gray scale and other charts. The field of view of the system is 1 x 2 cm; the spatial resolution is better than 100 microns. The red, green, and blue images can be used to reconstruct a color image of the flame using an appropriate algorithm based on the calibration. Although the flames are expected to be mostly blue in color, detection of soot, if any is present, is desirable. The intensities of the OH and CH images will be treated as qualitative measures of the strength of the reaction. The camera was tested in NASA Learjet flights in which the images were recorded onto videotape and later digitized for analysis and color reconstruction.

High speed, intensified video cameras were used in the laboratory to study the behavior of high-Lewis number premixed flames in tubes (ref. 5). New phenomena, such as spiral waves and radial pulsations, were observed that are not visible to the naked eye or at standard video rates of 30 frames per second. Others employed such a camera to track particles floating on a liquid fuel surface ahead of a spreading flame and found liquid motion in regimes where it had not previously been seen (ref. 6). High speed video framing rates of monochrome images can be acquired at up to 1000 frames per second for a full frame, or up to 6000 frames per second for 1/6 of a frame. The length of time of the recording depends upon the amount of storage for either tape (30,000 frames) or electronic memory (as high as 4600 frames). These cameras have also been used for other aerospace applications.

Infrared Imaging

Two-dimensional infrared cameras, based on platinum silicide, indium antimonide, or other infrared materials, have recently been used in reduced-gravity experiments. Such cameras image spectral regions of infrared emissions. For some systems, the use of narrow bandpass filters permits selected species to be detected. For others, the infrared images can be used as a surface temperature measurement.

An infrared camera, along with a rotating filter wheel, will be used to obtain species-specific radiation levels for the burning polymethylmethacrylate experiment mentioned above. The filters correspond to carbon dioxide (4.2 micron), water (1.8 micron), carbon monoxide (4.8 micron), methylmethacrylate vapor (3.4 micron), and soot (1.6 and 3.8 micron). The bandwidth of each filter is selected to match the signal sizes in each band and minimize saturation of the camera signal based on aircraft tests and model predictions. The camera will be calibrated against a black-body source so that the images can be quantitatively compared. For this experiment, the camera field of view is 3 x 2 cm for each of two images; the array is 256 x 256 pixels.

A system capable of obtaining spatially- and spectrally-resolved images is being built under a Phase II Small Business Innovative Research program contract. The initial instrument will have a bandpass between 2.4 and 3.2 microns dispersed by a grating across a 128 x 128 indium antimonide focal plane array. A scan mirror sweeps across the object of interest and the fore optics image a vertical slit onto the grating. For each video frame, the focal plane array detects a dispersed spectrum in the x-direction and position in the y-direction. A data cube consists of x, y, and wavelength (128 x 128 x 128) and can be taken once every 1.5 seconds. Data collection and storage is accomplished using a personal computer and a specialized I/O board. Data analysis will be conducted on a UNIX workstation using software written to use a commercial visual data analysis program.

Temperature measurements of the surface of a liquid pool ahead of a spreading flame were recorded with an infrared camera (ref. 6). The camera is sensitive to wavelengths between 3 and 12 microns, but for this case, a filter restricts the wavelength range to between 8 and 12 microns. The alcohol fuel is essentially opaque in this wavelength region so that the radiant emission reaching the camera comes from the surface layer, not the bulk fuel. The camera records monochrome images at normal video framing rates onto videotape. The temperature span chosen on the camera depends on the expected range of temperatures. During data analysis, the images are converted to false color and an absolute temperature scale is determined. This system has been used successfully aboard a sounding rocket.

Fluorescence Imaging

Although laser-induced fluorescence, LIF, imaging of radical species such as OH and CH is highly desirable, to date, this has not been performed in microgravity primarily because of the size and power limitations of the excitation laser sources. As the size of laser systems continues to decrease, radical species imaging becomes more feasible. Experiments in the laboratory using a new, solid-state laser source based on titanium:sapphire showed that laser-induced fluorescence point measurements on CH radicals can be made. As a step in making fluorescence measurements in microgravity, laser-induced fluorescence imaging of sodium doped into a burning droplet was performed on the NASA Learjet (ref. 7). The output of a small nitrogen-pumped dye laser at 589.6 nm was imaged into a thin sheet and directed across the top of a droplet. An LIF image was collected by an intensified CCD camera and, simultaneously, a second CCD camera detected the natural flame luminosity. Both video signals passed through time code generators to allow for a frame-by-frame comparison of the LIF and natural flame luminosity images.

Schlieren Imaging

The schlieren method is one of the oldest and simplest methods for visualizing refractive index inhomogeneities, such as those arising from temperature and species distributions. The refractive index gradients cause light rays in the test section to undergo angular deviations which are encoded by a suitable spatial filter into a detectable change in intensity, color, or other parameter. Schlieren has been employed primarily as a qualitative visualization tool, but with the development of the rainbow schlieren technique, quantitative measurements of the refractive index distribution may be made.

Gray-scale laser schlieren with video recording and subsequent digitizing and image processing was used (ref. 8) in the study of premixed laminar and turbulent flames in normal and reduced gravity. A 5 milliwatt HeNe laser was expanded to fill a 75 mm field of view. A compact monochrome CCD camera with a fast shutter speed detected the laser light after a 1.5 mm diameter dark field spot. Only the regions of light deflected by a refractive index gradient in the flame cone pass around the stop and were detected as bright regions on a black background. An Abekas-based editing facility at Lewis digitized the frames to have 512 x 512 pixel resolution. Since each video frame was captured in individual fields at 1/60 of a second, the frames were broken apart into odd and even fields having 512 x 256 pixel resolution. Several standard image processing techniques such as time sequencing, line representation, and Fast Fourier Transform, were used to further analyze the data to extract information such as gross features and flame flickering frequencies.

Quantitative schlieren measurements are based upon having a known relationship between the refractive index distribution and the angular ray deflections. For systems possessing simple or axisymmetric geometries, inversion of the data to obtain the refractive index distribution from the measured ray deflections is straightforward. The use of a continuously graded color filter, or rainbow filter, along with a stable light source and CCD camera minimizes the problems of nonuniform absorption, shadowgraphy, diffraction of the source image around a hard schlieren stop, and inherent nonlinearities in film recorders. The angular ray deflections are encoded as shifts in color attributes, specifically the hue, which can be reliably and accurately detected in an automated fashion (ref. 9). Quantitative laboratory calibration and demonstrations of the schlieren system were performed on a gas wedge, optical flat, and radiantly heated liquid pool.

In reduced gravity aboard the NASA KC-135A, rainbow schlieren systems were used to study flame spread across thin solid surfaces and isolated droplet combustion. More recent are sounding rocket studies of the flame spread across liquid pools and 2.2 sec drop tower studies of nonsooting diffusion flames. The liquid pool experiment system has a field of view of 100 mm. The color filter has a continuous hue variation in the horizontal direction across a span of 10 mm. Liquid temperature gradients over a 2 cm path length of ± 20 °C/cm were resolved; the smallest resolvable gradient is 0.07 °C/cm. The data can be integrated to obtain a map of the temperature distribution in the liquid or gas. The study of nonsooting hydrogen diffusion flames determined the near-nozzle flow structures of these extremely dim flames.

Imaging of Soot

A measurement of significant interest is that of the total amount of soot in the flame, or the integrated soot volume fraction. Traditionally, single line-of-sight absorption measurements using a narrow light source, such as a laser, and a single-element detector are used with traversal over the flame. A new method more suitable for microgravity where space and time are limited is based on imaging absorption of a laser light source with a CCD camera (ref. 10). Light from a low power HeNe is expanded, collimated, and directed through the test section. A lens and camera detect the light through a bandpass filter that rejects the flame

luminosity and transmits the laser light. The amount of light absorbed or scattered by the soot in the flame is measured by comparison to a reference frame taken without the flame. A deconvolution algorithm based on the Abel transform is used to invert the data for axisymmetric systems. The minimum absorptivity seen in a laminar diffusion flame in practice to date is approximately 2%. A study of different laser beam configurations, smoothing algorithms and kernels, and camera integration periods was undertaken to understand and minimize the effects of spatial noise and beam steering.

An alternate way to measure the soot volume fraction is by the use of laser-induced incandescence, LII. This process occurs when intense laser light heats the soot to temperatures far above the background. In accord with the Planck radiation law, the particle thermal emission at these elevated temperatures increases and shifts to the blue compared to the non-laser-heated soot and flame gases. Measurements in the laboratory show that the LII signal is linearly proportional to the soot volume fraction and may be easily interpreted as a relative measure of soot volume fraction (ref. 11). Absolute calibration of the technique may be made by *in situ* comparison of the LII signal to a system with a known soot volume fraction. LII offers high temporal resolution by obtaining signals induced by a single laser pulse. The laser may be formed into a sheet for imaging measurements. In the laboratory, one- and two-dimensional imaging measurements of premixed flames, gas jet diffusion flames, and isolated burning droplets were performed using a gated, intensified array camera.

Most nonintrusive measures of soot temperatures using multiline emission methods are based upon points in the flames being studied by traversal of the light source and detector. A new method uses a CCD camera system to image the entire flame, in this case a laminar diffusion flame, and with deconvolution procedures, alleviates the need for moving parts. Evaluation by comparing soot temperatures measured using three separate line pairs and by comparing the multiline temperature distribution with conventional thermocouple temperature measurements made in nearby soot-free regions of the flame showed that with the CCD system there was good agreement between the average of the three line pairs and each of the three line pairs, and that the best results were obtained when the line pairs were separated by more than 150 nm. This system is being implemented into a 2.2 sec drop rig and also is scheduled for a spaceflight experiment in 1997 to study sooting processes in laminar diffusion flames.

Image Processing and Tracking

An image processing and tracking workstation has been set up at NASA Lewis to assist in the data analysis of objects on recorded film or video tape. System components include film and video tape transports, personal computer, frame grabber, laser disk drive, high resolution video monitor, hard copy devices, and access to the Internet for file transfer to remote sites. Images on 16 and 35 mm film, S-VHS or Hi-8 mm video tape, laser disk, or TIFF and other image files can be analyzed. For film digitizing, a digital camera having a resolution of 1280 x 1024 pixels images the film directly. A 2:1 optical zoom enables imaging of a sub-region to an equivalent resolution of 2560 x 2048. A frame grabber digitizes and displays up to 1280 x 1024 pixels, with 8 bits each in the red, green, and blue colors. Image processing is performed on an area of interest which includes the desired object to be tracked to aid in the process. The processing algorithms include filtering, edge detection, thresholding, histogram equalization, and correlation. Recent examples of investigations using this workstation include the tracking of flames spreading between parallel solid surfaces, flame spread across liquid pool surfaces, candle flames, solid surface combustion of paper, and measuring the relative droplet-to-gas velocities during free float periods in microgravity.

Summary

An overview of the imaging techniques implemented by researchers in the microgravity combustion program shows that for almost any system, imaging of the flame may be accomplished in a variety of ways. Standard and intensified video, high speed, and infrared cameras, and fluorescence, laser schlieren, rainbow schlieren, soot volume fraction, and soot temperature imaging have all been used in the laboratory and many in reduced-gravity to make the necessary experimental measurements.

References

1. Weiland, K. J., "Intensified Array Camera Imaging of Solid Surface Combustion Aboard the NASA Learjet," *AIAA Journal*, Vol. 31, 1993, p. 786-788.
2. Ronney, P. D., Whaling, K. N., Abbud-Madrid, A., Gatto, J. L., and Pisowicz, V. L., "Stationary Premixed Flames in Spherical and Cylindrical Geometries," *AIAA Journal*, Vol. 32, 1994, p. 569-577.
3. Williams, F. A. and Dryer, F. L., "Science Requirements Document for the Droplet Combustion Experiment," 1994.
4. a. Altenkirch, R. A., Olson, S. L., and Bhattacharjee, S., "Science Requirements Document for the Diffusive and Radiative Transport in Fires Experiment," 1994.
b. Melikian, S., "Intensified True Color Imaging," NASA TM in preparation.
5. a. Pearlman, H. G. and Ronney, P. D., "Self-organized spiral and circular waves in premixed gas flames," *Journal of Chemical Physics*, Vol. 101, 1994, p. 2632-2633.
b. Pearlman, H. G. and Ronney, P. D., "Near-limit behavior of high-Lewis number premixed flames in tubes at normal and low gravity," *Physics of Fluids*, Vol. 6, 1994, p. 4009-4018.
6. Miller, F. J. and Ross, H. D., "Liquid-Phase Velocity and Temperature Fields During Uniform Flame Spread over 1-Propanol," *Eighth International Symposium on Transport Phenomena*, San Francisco, CA, 1995 (submitted).
7. Winter, M., "Laser Diagnostics for Microgravity Droplet Studies," AIAA Paper 94-0431, 32nd Aerospace Sciences Meeting & Exhibit, January 10-13, 1994, Reno, NV.
8. Kostiuk, L. W. and Cheng, R. K., "Imaging of premixed flames in microgravity," *Experiments in Fluids*, Vol. 18, 1994, p. 59-68.
9. Greenberg, P. S., Klimek, R. B., and Buchele, D. R., "Quantitative Rainbow Schlieren Deflectometry," *Applied Optics*, Vol. 34, 1995 (in press).
10. Greenberg, P. S. and Ku, J., "Soot Volume Fraction Imaging," *Applied Optics*, in preparation.
11. a. Vander Wal, R. L. and Weiland, K. J., "Laser-Induced Incandescence: Development and Characterization Towards a Measurement of Soot Volume Fraction," *Journal of Applied Physics B*, 1995, (in press).
b. Vander Wal, R. L. and Dietrich, D. L., "Laser-Induced Incandescence Applied to Droplet Combustion," *Applied Optics*, Vol. 34, 1995, p. 1103-1107.