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LASER DIAGNOSTICS FOR MICROGRAVITY DROPLET STUDIES

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Introduction

One of the most fundamental distinctions in combustion is whether a flame is a premixed or non-premixed flame. Condensed-phase materials usually serve as reactants in practical combustion devices, either through direct injection of a condensed-phase fuel into a combustor or the initial presence of a condensed-phase fuel within the combustor. These fuels generally burn as non-premixed flames. Additionally, most hazardous flames are multi-phase diffusion flames as well. Several of these combustion systems involve burning liquid-phase fuels which are comprised of numerous individual droplets.

Basic understanding is best advanced by well-controlled experiments and simplified calculations. A great deal of attention has been paid to studying the combustion of individual droplets,[1,2] which is the simplest example of non-premixed combustion. These single-droplet flames provide an idealized geometry for investigating the interaction of the physical and chemical processes involved. The importance of droplet vaporization and combustion was recognized as early as 1953,[3,4,5] and several reviews[1,6-10] describe the progression of this work. A significant means of simplifying droplet combustion is to approach the phenomena in a microgravity environment. A great deal of activity is ongoing in this area, including calculations, drop towers, the Droplet Combustion Experiment (DCE), and glove-box experiments aboard the space shuttle. Drop tower data have shown deviations from calculated results, suggesting that the experimental conditions may differ from the idealized assumptions used.

Optical diagnostics offer several advantages over physical probes because they permit nonintrusive multi-point measurements. Nonintrusive measurements are of particular importance for droplet combustion and transport in microgravity environments, where physical contact would introduce an unacceptable level of perturbations. The resolution of these diagnostics can also isolate transport to length scales much smaller than the droplet diameter. These techniques can be configured to instantaneously map an entire flow field in two and three dimensions, providing either qualitative or quantitative information on the distribution of a desired scalar or vector quantity.

The classic model of droplet combustion in the absence of gravity assumes the inner core contains the liquid fuel. Beyond a diameter d_l, there is a symmetric vapor cloud. Around the fuel exists an envelope flame at radius d_f. Energy is radiated both toward and away from the droplet center while combustion products flow out and oxidizer flows inward. Other assumptions include spherical symmetry, an isolated droplet in a quiescent medium, diffusion controlled rates, a single component fuel, and thin reaction zones.

Discrepancies between model predictions and experimental data have been observed in steady burning, convective transport, and microexplosions, to name just a few. These observations can be linked to the hypothesized responsible mechanisms including:

1. Unsteady or quasi-steady flame front position,
2. relative droplet/gas phase motion,
3. transport and condensation of pyrolitic products onto the droplet surface, and
4. convective transport within the droplet.

Approach

Flame Front and Velocimetry

A research requirement would be detailing the gas-phase flow field and position of the flame front. This can be achieved using PLIF of OH[11] or another flame front marker which is typically performed by tuning a laser to the molecular absorption and recording the emitted radiation with a two-dimensional detector. Laser sources and detection systems capable of operating under the power and shock environments typical of flight conditions are now available. An alternative approach, which is reported here is to obtain LIF from a diagnostic seed included in the liquid-phase fuel; it would be consumed at the flame front. The main advantage to this approach is that it is easier to choose the wavelength of the molecular absorption which coincides with convenient laser wavelengths rather than finding lasers which can be configured to access OH. Our present method uses a nitrogen-pumped dye laser tuned to a sodium absorption and addition of small concentrations of NaCl to the fuel. This will be described in more detail below.

PIV is a laser-based technique which has recently had its practicality greatly enhanced by the development of high-resolution CCD cameras and the increase in speed and capacity of computer systems. With this technique, a seeded flow is illuminated with a double-pulsed laser sheet to generate a double exposure image on a film or CCD camera. Computer analysis of the image is used to determine the particle velocity vectors and, thus, the gas velocity within the plane of the laser sheet. Our current experiment uses PIV for measuring relative droplet gas-phase velocities in a parabolic flight environment.

Experimental Methods and Design

UTRC under contract with NASA beginning in October of 1992, has designed and built an apparatus for performing measurements aboard the NASA Learjet, DC-9 and KC-135 aircraft facilities. An integrated diagnostic unit, capable of performing these measurements has been assembled. A new ND:Yag laser is currently being incorporated into the system. The system remains operational and flight ready; low gravity testing was performed.

Package

An overview photograph of the apparatus is shown in Fig 1. The system currently contains a nitrogen pump laser, tunable dye laser, two camera systems-one intensified, two time code generators, two VCRs, a Macintosh IIci computer with image digitization hardware and experiment control software, timing electronics, and power distribution. The package also contains a windowed combustion vessel capable of a wide range of pressures.

Controls

Droplet combustion occurs within the combustion vessel that houses the remote control systems on an internal multi-level platform consisting of triangular sections and threaded rod. In the center resides a fiber droplet holder surrounded by the droplet deployment and ignition hardware. The multi-level platform is complete with servo-actuators capable of deployment of a droplet onto a fiber, removing the deployment needle, introducing and energizing the igniter, igniting the droplet, and retracting the ignitor, all through remote operation via the control system joysticks and switches on the control box. A CCD video camera is used to monitor the procedure, and the images are displayed on a 2 in. LCD monitor attached to the control box. A second 2 in. LCD monitor is attached to the control box to display the images from the intensified CCD camera recording the PLIF or PIV data. In order to comply with power, size weight and cost budgets, the monitors used are commercial-grade miniature color television sets that have been modified. The controls box joysticks and actuators are modified radio controlled airplane equipment. The control system box can be seen in the top of Fig. 1.

A second multi-level combustion platform is available that includes a levitator. This module is a direct replacement to the original and can be replaced in a matter of minutes between tests. The design relies on electrodynamic levitation and the electrostatic levitation electrode are passive. While this increases the difficulties associated with 1-g testing, it significantly increases the optical access and precludes flame interferences at 0-g where the flame stand off distances are much greater. Plans for flying the levitator module aboard parabolic aircraft have been initiated.

Laser/Camera

Advanced laser diagnostics involving imaging of fluorescence fields, typically rely on high-power lasers, and sophisticated and extremely sensitive camera systems. The current NASA/UTRC flight apparatus uses a pulsed nitrogen laser that produces 0.3 mJ at 337 nm in a 3 ns pulse. This laser is used to pump a tunable dye laser providing a 30% pumping efficiency into a visible wavelength. The current experiment uses the laser system to provide either one pulse at 589 nm for PLIF of sodium, or, two pulses in sequence for PIV using elastic scattering from seed particles.

Two camera systems are currently housed in the flight apparatus. One is an intensified, cooled CCD capable of external triggering. Maximum data readout is 30 Hz, however, the system is operated at 20 Hz to achieve synchronization with the laser pulsing frequency. For PIV the intensifier is gated twice for every CCD frame readout event. A second CCD camera is used for observing droplet loading and ignition, and recording the flame luminosity during a burn. Both cameras are provided with microscopic optics to resolve both the droplet and surrounding flow field. The images from both camera are passed through synchronized time code generators which superimpose a time code signal on the images. This allows later comparison between the luminosity and the PLIF signals on a frame by frame basis. This can be important since all previous measurements of the flame behavior in microgravity droplet combustion relied on recording the flame luminosity. The time coded images are then recorded on highband 8 mm videocassettes for later analysis. The PLIF signals are also recorded through a frame grabber resident in the Macintosh IIci included in the flight rig.

Results and Discussions

PLIF from burning droplets under microgravity conditions was extremely successful. The nitrogen-pumped dye laser was formed into a sheet <250 μm wide and directed across the top of the droplet. The dye laser was tuned to 589 nm to pump sodium as described above. The laser-induced fluorescence was recorded in two-dimensions. Figure 2 shows a comparison of the laser-induced fluorescence image along with the luminosity image from the exact same instant in time. The luminosity image displays the full spherical envelope flame around the droplet while the PLIF image only provides flame position information over the droplet. The PLIF image however, only corresponds to a 3 ns instant in time corresponding to the laser pulse duration while the luminosity image is temporally integrated over the video frame time.

Video imaging of the flame luminosity gives a spatially integrated view, of the outside limit of the reaction zone. While the temporal resolution provided by a video camera frame time might be adequate under droplet combustion conditions, the lack of spatial resolution in such a measurement can be misleading. The video image will record the projection of this flame shell in two dimensions. The outermost position of the flame front is ascertained based on the region with the highest intensity, which may or may not correspond to the great circle, or equator of the droplet. Using the position of the highest intensity may also be misleading because for all locations other than the great circle, the camera will record two flame front positions, one in front of and one behind the actual circle of interest. In fact only at the one location which is of primary interest along that great circle will the luminosity be under represented, leading to an underprediction of flame diameter.

Using laser-induced fluorescence the spatial resolution into and out of the plane of the image corresponds to the thickness of the laser sheet. In our experiment a thin (~250 μm) laser sheet is directed across the top of the droplet at precisely the greatest diameter, (i.e. the equator). The information relating to flame front position from sodium fluorescence can only correspond to that spatial position regardless of the depth-of-field of the imaging system. It further eliminates the ambiguities associated with assuming the highest intensity marks the flame position.

PIV was also attempted and early data analysis suggests that these experiments were less successful in combusting environments. Adequate seeding densities were achieved using .9 μm silica particles. The particles were entrained into the flow ~15 seconds prior to initiating a trajectory by providing pulses of air through the chamber. Prior to ignition and in the absence of combustion, double exposures of the particles were recorded corresponding to two laser pulses. These data have been processed to provide the gas-phase flow field. Upon ignition the heat release and corresponding gas expansion propels the PIV seeds out of the measurement volume. When the droplet combustion is complete the particles immediately return to the measurement volume. From this we conclude that while PIV is applicable in general to microgravity studies and can successfully be applied in this environment, it may not be appropriate as a microgravity combustion diagnostic. This can be contrasted with one-g combustion where PIV has successfully been applied since the dominant flow mechanism is convection, which carries the PIV seed particles into the region of interest. Another interpretation of this result might be that radial outflow dominates droplet combustion.

Successful radical chemiluminescence, PLIF and visible flame luminosity images were obtained. Initial analysis indicates that the broadband visible flame luminosity and radical chemiluminescence agree well in mapping the flame front position. The resulting data were processed to provide information on droplet regression rate and flame diameter as a function of time. These data are shown in Fig. 3 where the results are shown for d^2 as a function of time for these luminosity, radical emission at 308 nm, and sodium PLIF. Similar behavior is seen for each. However, the luminosity consistently over predicts the flame diameter relative to the radical emissions and PLIF data. The flame position as determined from the PLIF is self consistent with the radical emissions. Future efforts will be directed at recording PLIF from OH radicals directly.

Conclusions

An instrument has been designed, built, and tested for performing laser diagnostic measurements of droplet combustion in low gravity flight aircraft. The results show successful application of PLIF relative to luminosity and radical emission near 308 nm. PIV results are less successful due to gas thermal expansion deflecting the seed particles away from the measurement volume. PIV is applicable for measurements in the absence of combustion. Further analysis and alternate seeding schemes are being explored.

The flight instrument embraces many new actuation and control schemes that proved successful in flight. The system has been designed for various other diagnostic measurements. Further experiments will investigate these as well as a range of droplet fuels and combustion under a range of pressure situations.

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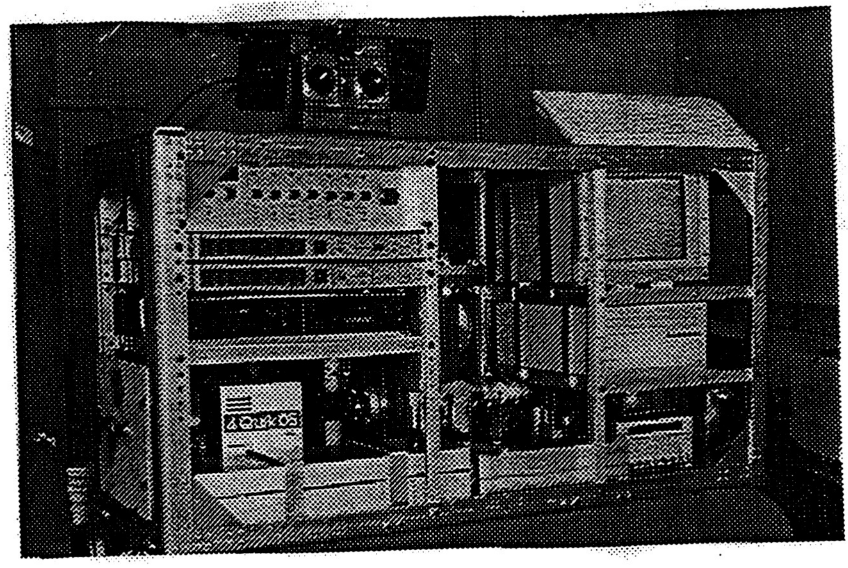

Figure 1. Photograph of the UTRC/NASA laser diagnostics for microgravity droplet combustion apparatus.

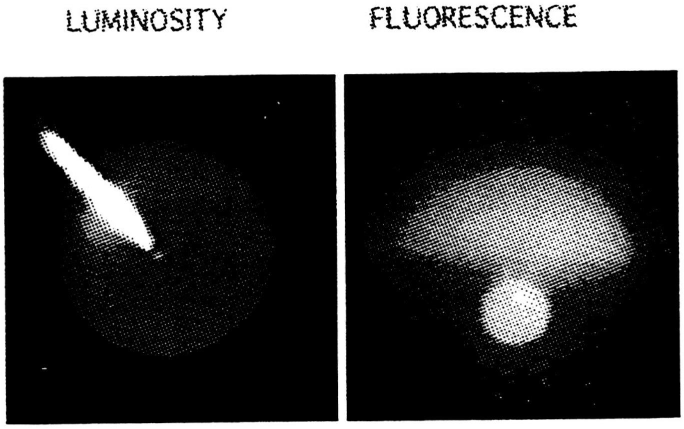

Figure 2. Comparison of PLIF of sodium and flame luminosity.

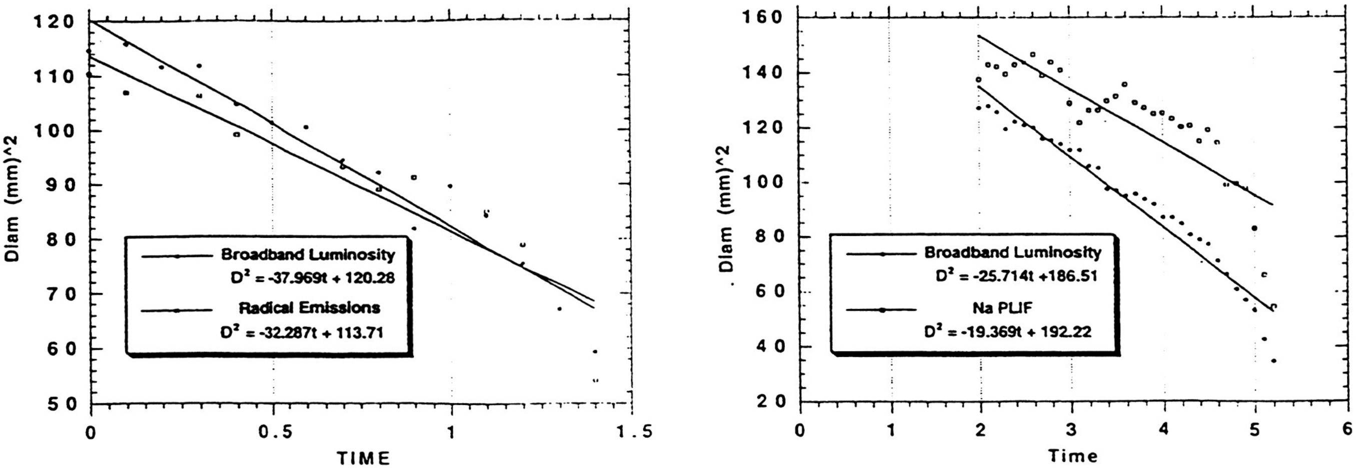

Figure 3. D^2 fit to broadband luminosity, radical emissions and sodium PLIF.