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LASER DOPPLER VELOCIMETRY AND FULL-FIELD SOOT VOLUME FRACTION MEASUREMENTS IN MICROGRAVITY

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Laser Doppler Velocimetry

Since its introduction in the mid-sixties,[1] laser doppler velocimetry (LDV) has become one of the most widely used methods for the measurement of flows. Its remote and essentially non-intrusive nature provides an invaluable tool for a variety of difficult measurement situations which would be otherwise inaccessible. The high spatial resolution and rapid temporal response afforded by this technique are well suited to the determination of spatial and temporal details of flow fields, as well as characterization of turbulence. Advances in the understanding of the properties of LDV signals, accompanied by technological advances in coherent laser sources, detectors of high sensitivity and low noise, optical fabrication techniques and high-speed digital signal processing architectures have resulted in systems of increased accuracy and flexibility. As will be shown, recent progress in solid-state lasers and photo-detectors have been beneficial insofar as the compatibility of this method with the unique and severe constraints inherent in microgravity combustion science experiments.

In brief, LDV relies on the doppler shift of optical radiation imparted by the velocity of the fluid flow.[2] Generally, this requires the introduction of small seed particles into the flow to serve as optical scattering centers. The size and mass of these seed particles must therefore be carefully considered to insure that their velocities are suitably indicative of the velocity of the fluid medium in which they are entrained. This property is usually expressed as the aerodynamic or hydrodynamic diameter of the particle[3] and is defined as the diameter of a unit density sphere possessing the same settling velocity as the particle in question. For the case of spherical particles, this expression simplifies to $d_a = a\cdot(\rho)^{1/2}$, where a is the actual diameter and ρ is the mass density. The frequency response of this equivalent particle is then evaluated for its ability to respond to flow-field accelerations. The relatively low velocities, moderate turbulence intensities, and large spatial scales in most microgravity combustion phenomena allow the use of larger particles. The result is large scattering cross sections, and thus acceptable signal-to-noise ratios in the presence of compact, low power laser sources and modest optical collection efficiencies. As an example, for a band-limited turbulent spectra of 10^4 Hz., a 1.0 micron particle yields a value of $(v_p/v_a) = 0.98$, where v_p is the particle velocity and v_a is the actual velocity of the fluid flow. At a maximum frequency of 10^3 Hz., this ratio is still achievable by the use of 5.0 micron particles.

Rudimentary analysis of a laser doppler signal demonstrates that the frequency of the incident radiation is doppler shifted by an amount $\Omega = \mathbf{K}\cdot \mathbf{v}$, where $\mathbf{K} = \mathbf{k}_s - \mathbf{k}_i$, where v is the velocity of the entrained particle, the latter quantities representing the wave vectors of the scattered and incident radiation, respectively. The most common physical realization of an LDV system is the so called dual-doppler, or fringe configuration. This is shown schematically in figure 1. The net result of the two incident beams can be thought of as producing a set of periodic fringes throughout the spatial volume defined by their intersection. Particles passing through this intersection region and traveling transverse to the orientation of these fringes produce a scattered signal whose periodicity is given by: The signal resulting from the passage of a single particle is referred to as a doppler burst; a burst produced from a

$$f = [\bar{v} \cdot \bar{K} / |K|] 2 (\sin\theta) / \lambda_l \quad (1)$$

typical LDV system is shown in figure 2. For most systems encountered in practice, the fringe spacing results in observed dual-doppler frequencies on the order of 10^5 to 10^6 Hz./meter/second.

The system represented in figure 1 is configured in a coaxial, backscatter arrangement. This affords two principal advantages: 1) the system is single-ended (i.e. the transmission and detection optics are on the same side of the test section), and 2) it is easier to maintain alignment of the transmission and detection sample volumes. The latter is attributable both to the more compact geometry and to the fact that the incident and scattered light traverse the same optical path. This eliminates problematic beam steering effects produced by refractive index gradients that are often present in the flow-field itself. The disadvantage of a coaxial backscatter configuration arises from the fact that differential scattering cross sections are peaked in the forward direction, thus overall collection efficiency is reduced. Again, for the velocity fields typical of microgravity combustion phenomena, this is not outweighed by the advantages of a backscatter configuration.

As previously indicated, technological advances in solid-state laser diodes and avalanche photo-detectors (APD's) have recently been utilized to construct compact, mechanically robust LDV systems. Such systems offer extremely modest electrical power consumption as well. Diode laser sources possessing reasonable coherence and geometric radiation properties are now routinely available on a commercial basis. Active temperature control circuitry is required, however, to provide modal stability. In contrast, more conventional LDV systems that use gas discharge lasers are too large, fragile, and consume too much power for reduced gravity applications.

High performance APD's and associated preamplifiers are now similarly available. Although photomultiplier tubes (PMT's) provide higher absolute gains, APD's are shown to be more suitable for this purpose due to their substantially larger quantum efficiencies (QE) (≈80% for an APD vs. ≈14% for a PMT). Because photon noise is given by $(n/QE)^{1/2}$, where n is the mean photon arrival rate, APD's provide a superior excess noise factor in this application, providing a three-fold improvement in signal to noise for peak scattered fluxes approaching 100 microwatts. APD's also require high voltage power supplies; incorporating this into a compact package while providing the necessary degree of shielding and isolation requires careful consideration. Additional improvement in signal to noise ratio is achieved by cooling the detector. Compact LDV systems of this type are presently being utilized in the Microgravity Combustion Diagnostics Development Laboratory at the NASA-Lewis Research Center. Shown in figure 3 is velocity field data from a non-reacting gas jet obtained with such a device. The doppler burst shown in figure 2 was also obtained with this system. The particular device used to collect this data measures 65 mm in diameter and 200 mm in length, and consumes approximately 12 watts of electrical power. Contained within this package are the diode laser source with active temperature control circuitry, the APD with the required high voltage DC-DC converter, a low noise preamplifier, and a 50 ohm line driver.

The relatively modest f numbers associated with these compact systems (≈f/6) decreases the spatial resolution of the sample volume in the axial direction. The axial extent of the sample volume is on the order of 1.5 mm for present systems, limiting the ability to perform measurements in close proximity to test section walls or other boundaries. Seasholtz, et al[4] demonstrated that considerable improvement can be obtained in this regard through improvements in the transmitting optics, and confocal masking.

Significant advances have also been made in the area of dedicated signal processors. To provide on-line estimates of velocity spectra at bandwidths typical of LDV signals, early counter-type processors relied on zero-crossing signal detection. Over the past several years, high speed digital signal processing architectures have enabled the calculation and subsequent parameter estimation of complete spectra, either in the form of Fourier spectra or temporal autocorrelation functions. Processors of this type have yielded a ten-fold improvement in the accuracy of the resulting velocity estimates, and are able to operate at lower overall signal to noise ratios.[5] A system of this type is being utilized in microgravity combustion science research at the Lewis Research Center, and provides several unique features relevant to this application. Specifically, this processor has been configured in the form of two 16-bit ISA cards for use in a conventional personal computer. This affords convenience and flexibility for utilization in the LeRC drop tower and aircraft facilities; it is also anticipated to be advantageous for space flight applications. Also included is the capability to function as a digital transient recorder. This is extremely valuable for drop tower and aircraft studies, allowing raw data to be acquired and archived for subsequent post-processing.

Soot Volume Fraction Imaging

Soot is of fundamental interest from the standpoint of fuel and combustor efficiency, hardware longevity, and its relationship to public health. A comprehensive understanding of soot formation, aggregation, and oxidation mechanisms is, however, far from complete. Details concerning precursor chemistry, morphology, and overall production rates (i.e. volume fractions) remain active areas of study. For more than a decade, optical extinction methods have been utilized as an important tool for the determination of soot volume fractions in combustion applications.[6,7] More recently, investigations have focused on providing detailed, spatially resolved measurements of soot particle concentration fields.[8,9] These techniques have benefitted from the availability of coherent, monochromatic sources (i.e. lasers), owing to their well defined spectral properties, critical to interpreting the spectrally dependent properties of carbonaceous soot itself and to the advantages afforded in optical beam conditioning and manipulation.

The analysis of optical extinction data involves the determination of local soot volume fractions from a set of integrated line-of-sight measurements. Assumptions required to validate the inversion of this data include parallel, chord-like ray trajectories, negligible refraction effects, no significant absorption or scattering from media other than soot particles, an absence of radiant emissions corresponding to the wavelength of the laser source, and a knowledge of the spectrally dependent scattering and absorption properties of the soot itself, and the optical path length through the soot-containing medium. The latter is usually handled by the selection of a combustion phenomenon possessing axisymmetry. Well known Abel transformation equations may then be invoked.

Given the above assumptions, the extinction of optical radiation due to the presence of soot may be expressed as:

$$\frac{dI_\lambda}{ds} = -k_{e\lambda} I\lambda \qquad (2)$$

where $k_{e\lambda}$ is the optical extinction coefficient evaluated at the wavelength of the source. Integration of equation (2) along chord-like paths through the flame yields the relation:

$$\ln(I_{\lambda 0}/I_\lambda) = \int_{-\infty}^{+\infty} k_{e\lambda}\, ds \qquad (3)$$

In the Rayleigh scattering limit, the volume fraction is then related to the extinction coefficient by:

$$f_v = \lambda k_{e\lambda}/(6\pi E(m)) \qquad (4)$$

where $E(m) = -\mathrm{Im}\,(m^2-1)/(m^2+2))$, m being the complex refractive index for soot particles. Spatially localized values of f_v are then obtained from equations (3) and (4) via tomographic inversion.

To date, studies have relied on sequential point-by-point interrogation of the soot field. Such methods are not well suited to investigations involving nonrepeatable time dependent or transient phenomena. In the context of microgravity combustion science, where constraints on overall experiment duration and/or available expendable resources are often encountered, this limitation can be difficult to overcome.

To address this need, a full-field, or image based technique was developed.[10] It provides the capability to perform measurements at 2.5×10^5 simultaneous spatial locations at a refresh rate of 30 Hz. The total field of view corresponding to this sample set is determined by the receiving optics. An appreciation for the benefits of this enhanced capability is immediate when viewed in the context of aircraft or drop tower tests; by using a point measurement technique, it would be difficult to obtain more than a few selected data points during the overall experiment run time. Given the desire to reach some reasonable approximation of steady-state conditions, the validity of temporal correlations between these individual data points would be questionable. Additionally, the value of an image of the complete soot field to qualitative understanding is immense.

Soot volume fraction data corresponding to a 3.85 cc/sec laminar ethylene diffusion flame is shown in figure 4. In this case, the burner is stabilized with an annular co-flow of air. Data obtained with this method are observed to be in close agreement with previously published experimental results obtained via pointwise measurements.[8] The present limitation of this technique is absolute sensitivity. The high temporal bandwidths required to sustain the described data rate of 7.5 megabytes per second provides a large noise equivalent power (NEP) as well. If overall data rate is preserved, a signal to noise ratio of one corresponds to a line-of-sight extinction value of roughly two percent.

Apparatus to perform soot volume fraction imaging has also been implemented within the relatively confined volume of a 2.2 second drop package. This does not include the provision for on-line data storage, which is presently accommodated by telemetric link. A comparison of soot volume fractions corresponding to a 1.5 mm laminar gas jet diffusion flame with a 50/50 [partial pressure] acetylene/nitrogen mixture operating under both normal and reduced gravity conditions is shown in figures 5 and 6. It can be readily observed that the soot shell occurs at significantly larger radii, and that the maximum value of volume fraction is approximately twenty percent larger under reduced gravity. Under these same conditions, the transmitivity is reduced by over forty percent, indicating a significant increase in overall soot production.

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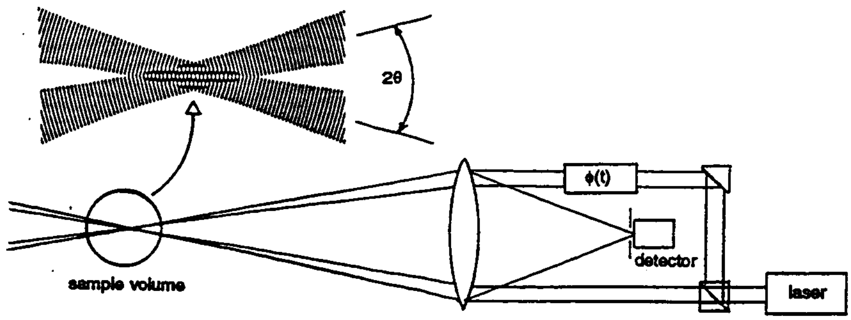


Figure 1: Schematic of dual-doppler LDV in backscatter configuration

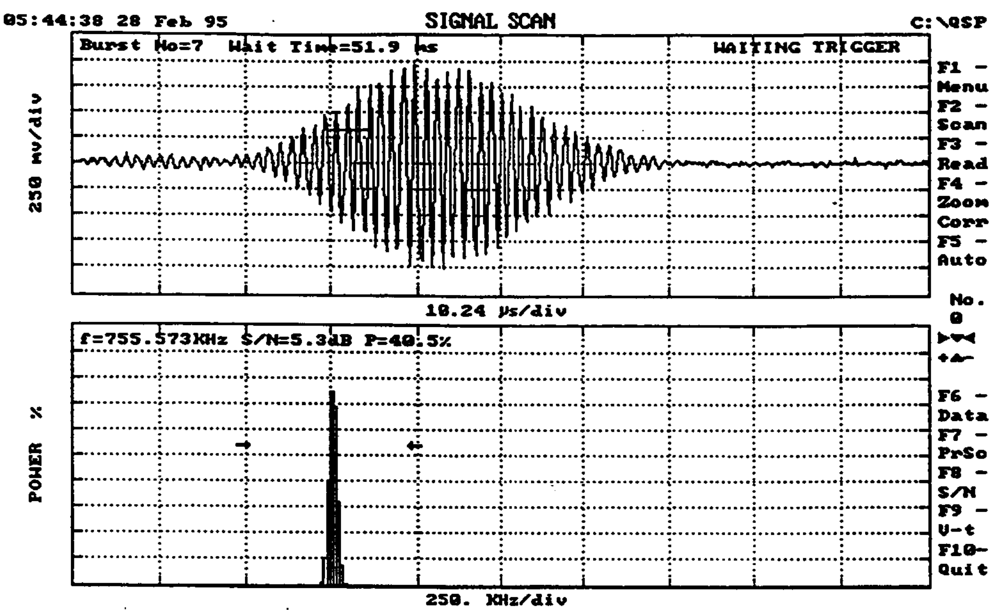
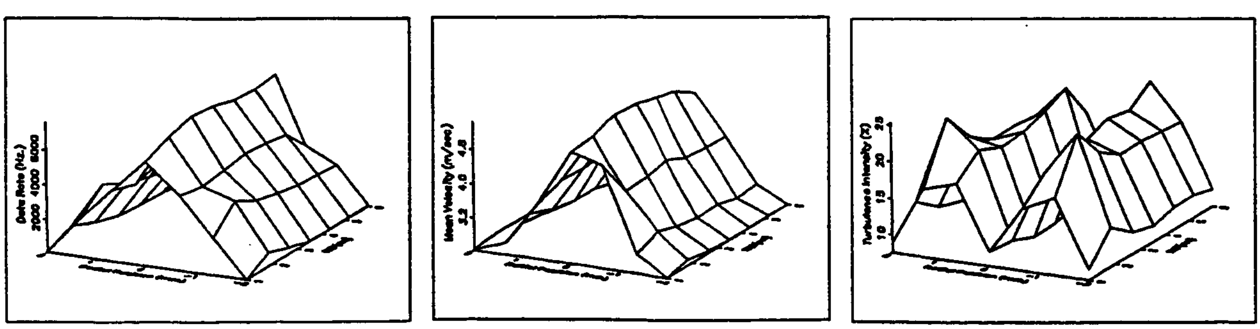


Figure 2: Single Doppler Burst from Compact, Solid-State LDV



Data Rate Mean Velocity Turbulence Intensity

Figure 3: Velocity Field of Re 1438 Non-reacting Jet

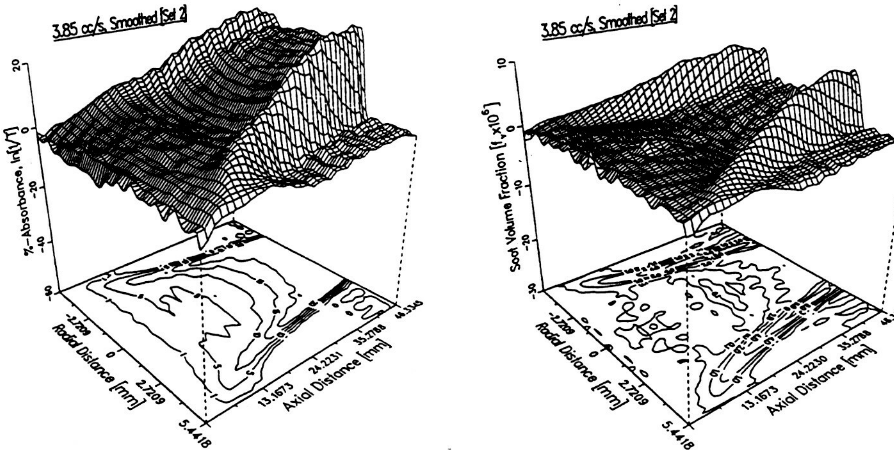


Figure 4: Absorbance and Soot Volume Fractions: 3.85 cc/sec laminar ethylene diffusion flame

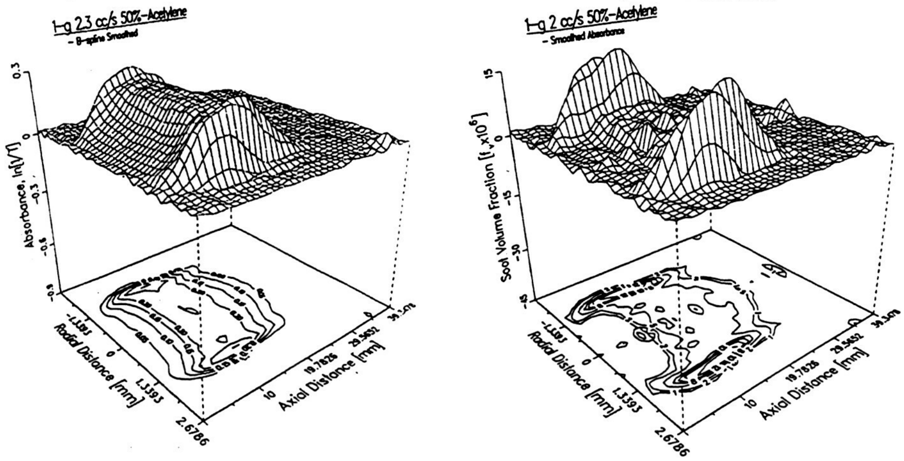


Figure 5: Absorbance and Soot Volume Fractions: 2.3 cc/sec laminar acetylene/nitrogen diffusion flame; Normal Gravity

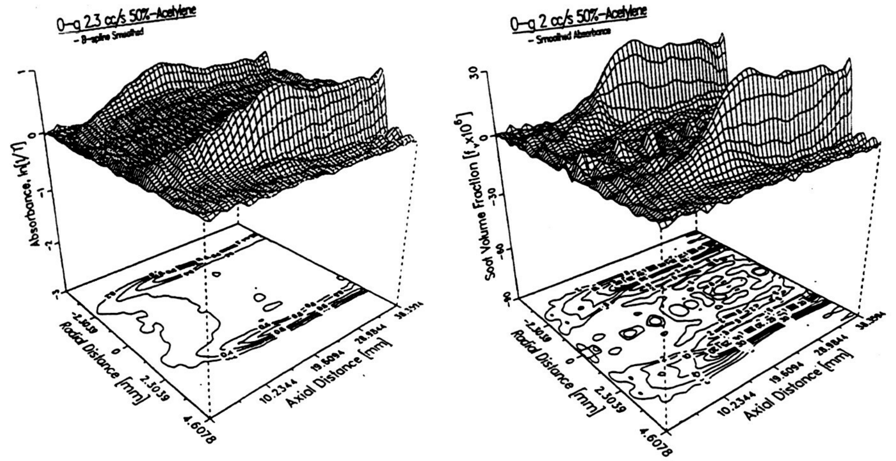


Figure 6: Absorbance and Soot Volume Fractions: 2.3 cc/sec laminar acetylene/nitrogen diffusion flame; ReducedGravity