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Non-contact Temperature Measurements in Support of Microgravity Combustion Experiments

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I. Introduction

Recent conceptual advances in the understanding of combustion science fundamentals in the context of microgravity processes and phenomenology have resulted in an increased demand for diagnostic systems of greater sophistication. Owing primarily to the severe operational constraints that accompany the space flight environment, measurement systems to date remain fairly primative in nature. Qualitative pictures provided by photographic recording media comprise the majority of the existing data, the remainder consisting of the output of conventional transducers, such as thermocouples, hot wires, and pressure transducers. The absence of the rather strong influence of buoyant convection renders microgravity combustion phenomena more fragile than their 1-G counterparts. The emphasis has therefore been placed on nonperturbing optical diagnostics. Other factors, such as limited supplies of expendable reactants, and periods of microgravity time of sufficient duration, coupled with more fundamental questions regarding inherent length and time scales and reproducibility have favored multipoint or multidimensional techniques. While the development of optical diagnostics for application to combustion science is an extremely active area at present, the peculiarities of space flight hardware severely restrict the feasibility of implementing the majority of techniques which are being utilized in terrestrial applications. The additional requirements for system reliability and operational simplicity have tended to promote somewhat less commonly emphasized techniques such as refractive index mapping and molecular Rayleigh scattering.

II. Refractive Index Mapping

The development of quantitative diagnostic tools for planar (2-D) measurements of temperature fields in gaseous flows is of significant interest in combustion science. For the most part, the development of 2-D measurement techniques has emphasized the application of Laser Induced Fluorescence (LIF) and molecular scattering processes (Raman and Rayleigh). These methods offer the advantages of spatial specificity (afforded by planar illumination) and species or transition specificity (with the exception of Rayleigh scattering). The relative weakness of these processes, however, places requirements on the optical source strengths which are, in many cases, incommensurate with presently envisioned spaceflight hardware. A number of tuned absorption techniques are also being pursued for this purpose, but are generally restricted to single-point realizations.

For these reasons, refractive index methods represent an attractive alternative for a number of applications. The emphasis is not being placed on interferometric techniques, however, due to their relatively severe mechanical stability requirements. In contrast, deflectometers tend to be less complex, less sensitive to vibration and misalignment, and more readily accommodating to large fields of view. In addition, it is possible to construct systems of suitable sensitivity to accommodate the majority of applications which are currently envisioned.[1] For situations involving gasses of known composition, the refractive index data can be directly related to specific parameters of interest, such as temperature and density.[2] More complex compositions must be addressed on a selective basis. Because of the line-of-sight nature of refractive index measurements, the initial application will be delegated to systems of known symmetry, thus eliminating the requirement for more complex multiple angle tomographic reconstruction procedures.

The first method to be pursued is an extension of the qualitative Rainbow Schlieren system which is currently being developed for flow visualization purposes. The continuously graded color filter offers several advantages over conventional knife-edge or slit systems.[3] Principal among these are a lack of stepwise discontinuities, and the use of color rather than intensity to encode deflection magnitudes. A two stage, folded catadioptric optical system has been designed to afford the desired optical performance in a fairly compact package (approximately 0.5 meters on a side). A schematic drawing of this configuration is shown in figure 1. A small zirconium arc lamp serves as the optical source. The spatial extent of the arc itself (approximately 0.010") is well matched to the corresponding dimensions of the rainbow filter, and its spectrum is relatively uniform over the range of visible wavelengths. The primary focusing elements are off-axis paraboloidal mirrors, which provide a true diffraction limited image of the source at all wavelengths. The secondary element is an asymmetric pair of Cooke triplets operating at a conjugate ratio of 1:10 at F4.

A true three-color solid state array detector with zero pixel offset will be employed as the imaging device. This detector is read by a three channel parallel digitizer which resides in a conventional laboratory PC system. Various basis sets for color representation are being pursued. Hue, saturation, and intensity (HSI) space appears the most promising at present, and should provide roughly 0.5% accuracies of resulting deflection magnitudes. Conventional integral transform methods will then be utilized to invert the measured ray deflection fields, yielding the desired refractive distributions.[4] The ability of the system to reconstruct specific refractive index fields will then be evaluated in the context of other previously demonstrated deflectometric methods, such as heterodyne Moire[5] and Wollaston full-field interferometry.[6]

III. 2-D Rayleigh Scattering

The need for nonintrusive methods of determining quantitative 2-D temperatures and gas concentrations has led to the development of various planar imaging techniques. As previously described, several methods have been recently demonstrated, utilizing both spontaneous Raman and Rayleigh scattering, as well as laser induced fluorescence techniques. While Raman scattering and induced fluorescence afford the advantages of species specificity, the requirements placed upon the optical sources are currently somewhat disadvantageous in the context of space flight applications. Raman scattering, for example, suffers from exceedingly small scattering cross sections, thus demanding unrealistically large input optical power levels. Fluorescence techniques are hindered by configurationally complex and, in many cases, inefficient conversion processes which are a necessary step in the generation of the appropriate source wavelengths. The relatively large signal strengths and wavelength independence of the source make Rayleigh scattering a potentially viable technique for these applications as rapid technological advancements begin to place new types of laser devices within reach.

2-D Rayleigh scattering methods have recently been demonstrated by a number of investigators.[7,8,9] In general, these methods are predicated on the linear relationship between the scattered power and the local gas density (i.e. the number of available scattering centers). In isobaric systems, this number density can, in turn, be related to the local gas temperature. The removal of the elastically scattered background contribution usually involves cumbersome in-situ calibration procedures. The test chamber or ambient region surrounding the apparatus must be either evacuated, or back-filled with an atmosphere whose cross section and number density are accurately known at two or more values in order for the background contribution to the scattered intensity to be determined explicitly.

Two approaches are being explored in which the effect of background contributions to the scattered signal can be removed without a priori calibration procedures: i) simultaneous multiple wavelength scattering and ii) spectrally resolved imaging interferometry. Multiple wavelength scattering exploits the specific dependence of the Rayleigh scattering cross section on wavelength. The other scattering processes which contribute to the total measured signal do not exhibit this functional dependence, and can thus be removed via a straighforward system of N algebraic equations (where N represents the number of discrete wavelengths being employed). This approach has been demonstrated for single point measurements using the two principal lines (510 578 nm) of a pulsed copper vapor laser.[10] Single point measurements of gas density to a predicted accuracy of 1.7% have been reported in a 1200^{o} K, 20 atm. environment. The decreased signal strengths resulting from near ambient pressure conditions will be offset by increased gate times. The initial application will operate at conventional video frame rates, which represent an increase in integration times of 2 x 10^{2}. A split imaging system will be constructed, wherein the field of view will be simultaneously imaged onto separate portions of the imaging array (see figure 2). Narrow line interference filters will be employed to achieve adequate channel separation. Although Rayleigh scattering is only applicable to gas temperature measurements if the effective cross section of the reactants and combustion products remains constant throughout the reaction, it has been shown that a variety of gas mixtures satisfy this condition to within a few percent.[11] In addition, more sophisticated models have been developed wherein the evolution of the scattering cross sections can be predicted as a function of the extent of the completion of the reaction.[12] Using such predictions, the change in cross sections can be incorporated into the data reduction procedures to achieve a more refined temperature measurement.

Spectrally resolved imaging interferometry will be employed to measure the Doppler-broadened linewidths of the scattered signal directly. The scattered linewidth depends on the temperature because the spectral broadening is caused by the Doppler shift from moving molecules. The translational velocity distribution giving rise to the observed shifts is in turn linked to temperature via the Maxwell-Boltzmann relationship. The background signal does not exhibit this broadening, and hence can be readily distinguished. The functional form of the measured spectrum is dependent on pressure. At low pressures (assuming noninteracting, randomly distributed particles) the spectrum has a Gaussian form. Higher pressure regimes require corrections to account for interparticle interactions. The association of the measured spectral width with temperature requires a knowledge of the molecular weights of the species present. As such, similar mixture tailoring procedures or additional information about the reaction chemistry are required for the total intensity measurements which have been previously discussed. Point temperature measurements using Rayleigh scattering line-widths have been previously reported,[13] and an a priori analysis indicates that accuracies of 10^{o} K are achievable in a

10 msec interval at 2000° K and one atmosphere, using an input power level of 1 watt at 488.0 nm. Spectrally resolved imaging interferometry as applied to remote thermometry has been reported by several investigators,[14,15] primarily for measuring auroral emissions. In recent years, flight-qualified versions of these instruments have been constructed, most notably for the Explorer space probe. Two methods of acquiring spectral data will be pursued. In the fringe or image mode, the spectral width is manifest by the local broadening of the fringe field. In the spectrally scanned mode, the center frequency of the interferometer is swept, yielding spectral signatures independently at each point in the pixel field.

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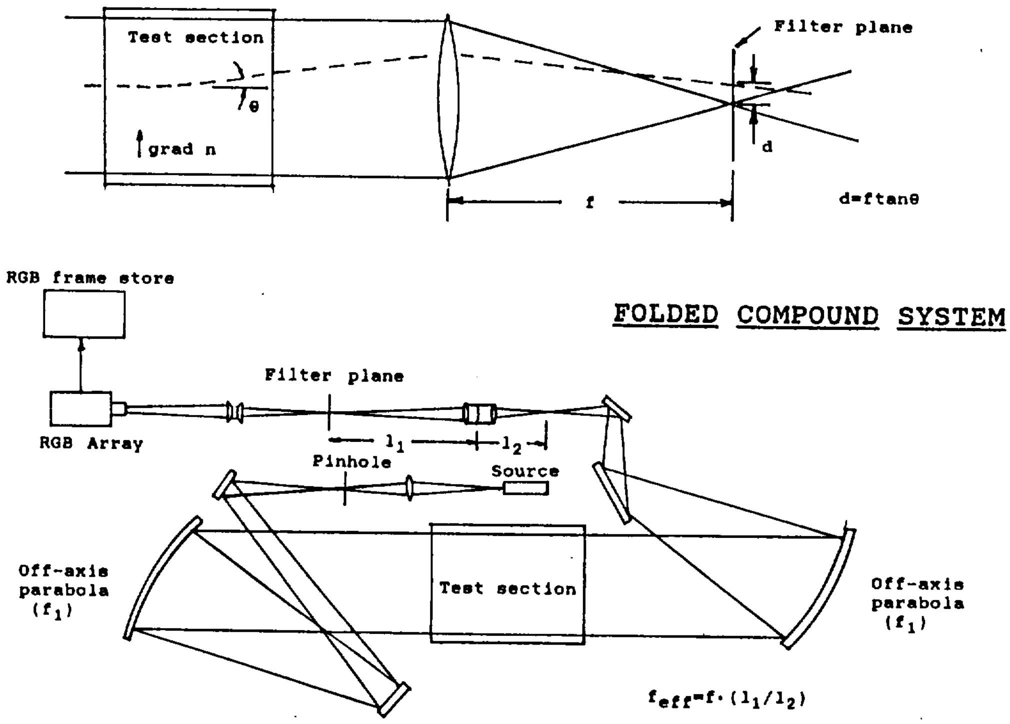

Figure 1. Operating Principle of Rainbow Schlieren

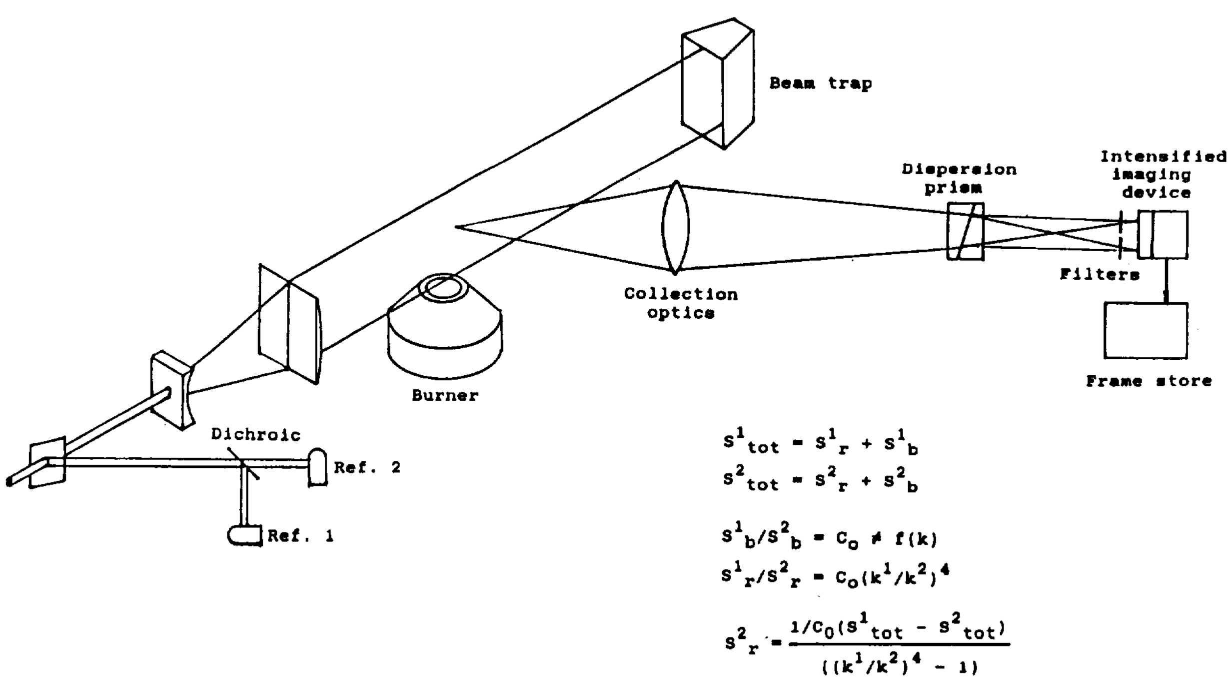

Figure 2. 2-Wavelength Rayleigh Scattering