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Flowfield Diagnostics

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The applicability of modern laser diagnostic techniques to measurements in a major part of the spectrum of experimental fluid mechanics is examined. In particular, an integrated system using the spontaneous Raman effect and the laser Doppler velocimeter are utilized. It is known that with this system, when a short duration laser pulse is used, simultaneous and instantaneous measurements of concentration and temperature of ionized as well as nonionized species in a flowfield are possible. In addition, velocity, turbulent intensity, and a number of correlation parameters are obtainable simultaneously and nonintrusively.

Nomenclature

C = experimental constant or specie concentration
c = speed of light
f_i = number of samples of the total number of observations
h = Planck's constant
I = intensity
k = Boltzmann constant
N = number of scattering species in volume or total number of data point
n_i = number of times i term occurs
T = temperature, K
u = velocity of the flow
X/D = axial location in jet normalized to inner jet diameter of coaxial jet
Z = radial location in jet
ν = wave number

Subscripts

AS or A = anti-Stokes line Raman scattering laser light
i = incident laser light
o = initial laser light
p = photon
s = Stokes line Raman scattering laser light
α = species α
β = species β

Superscripts

$(\bar{\ })$ = mean quantity
$(\ )'$ = fluctuating quantity

Introduction

THE development of reliable and nonintrusive diagnostic methods for flowfields under adverse environmental conditions has been the aim of continuing investigations for a number of years in our own and many other laboratories. The emergence of the laser resulted in a giant surge in the development of modern nonintrusive diagnostic techniques. Some of these are capable of providing all of the required information pertaining to flowfields, instantaneously, simultaneously, and remotely.

The density, temperature, and velocity are some of the most important variables which, in conjunction with other derived parameters, may be used to describe a flowfield completely. The problem of measuring these variables may present serious difficulties, not only when one is attempting to obtain measurements in a nonintrusive manner, but even when one is attempting to obtain measurements using standard diagnostic techniques. The difficulties depend, among others, on the environmental aspects of the flowfield under investigation.

In this paper some modern diagnostic techniques associated with scattering of incident laser light are discussed. In this context two aspects of laser light scattering are being emphasized, one dealing with elastic scattering as the basis of the laser doppler velocimeter (LDV) techniques, and the other dealing with inelastic scattering as the basis of the Raman diagnostic technique. Most of these developments appeared in the literature. The number of publications concerning these techniques and diagnostic methods is too voluminous to discuss or list here. It should, however, be pointed out that as a result of the workshops and symposia held over the last few years, several books have appeared that are collections of papers and discussions on the preceding technologies.[1-4] More recent publications on the subject may be found.[5-10] In this work some experimental results as obtained on a coaxial turbulent diffusion flame, utilizing the single high-power laser pulse technique in combination with the LDV, which has been incorporated into the diagnostic system are presented. In addition, ionized specie concentration and temperature behind a reflected shock using the spontaneous Raman effect is experimentally determined. It is also shown that the short-duration high-power laser pulse technique, because of its inherent properties of permitting simultaneous and instantaneous concentration and temperature measurements of a number of species, may be able to provide information concerning density and temperature fluctuation and possibly cross correlation information, or in the case of reacting flows the "mixedness" parameter.

Theoretical Background

The theoretical background of the Raman scattering techniques as well as the laser Doppler velocimeter techniques is presented adequately in the previously cited references. It is therefore sufficient here to recall the basic governing equations concerning specie concentration and temperature measurements by means of the Raman effect and velocity measurements by means of the LDV techniques. Thus, the concentration of a given specie in a mixture may be obtained from the intensity of the vibrational Stokes or anti-Stokes line of the scattered laser energy by the specie of interest:

$$I_{s,A} = CNI_0(\nu_0 \pm \nu)^4 \left[1 - \exp\left(-\frac{hc\nu}{kT}\right)\right]^{-1} \tag{1}$$

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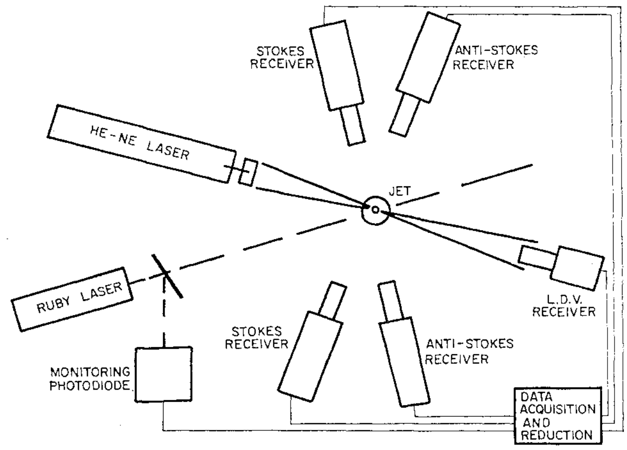

Fig. 1 Block diagram of experimental apparatus.

To obtain the temperature one may use the ratio of the Stokes to anti-Stokes intensity for a given specie, which at equilibrum taking account of the Boltzmann factor results in

$$T=\frac{h\nu c}{k}\left[\ln\frac{I_s}{I_{AS}}+4\ln\left(\frac{\nu_0+\nu}{\nu_0-\nu}\right)\right]^{-1} \tag{2}$$

One may also obtain the temperature from the ratios of intensities of rotational lines, or from the hot bands of the resolved Q-branch of the vibrational lines. These and other methods of temperature measurement using the Raman effect are discussed in the cited references. In any case, it is clear from Eqs. (1) and (2) that the concentration and temperature of a specie in a flowfield is measurable nonintrusively, and when a high-power short-duration laser pulse is used, instantaneously and simultaneously.

As far as the LDV is concerned, it is well known that the theoretical basis for this technique is the Doppler effect. As indicated previously in Refs. 1 and 2 and many others too numerous to list, this technique is now becoming a standard laboratory feature. Assuming that all of the conditions for proper operation of the LDV are met, including the proper number and size of the scattering particles in the scattering volume, the velocity measurement is reduced to a frequency measurement.

The velocity signals obtained from frequency signals processed appropriately can be stored in the form of a histogram in the memory of an on-line computer and later processed to yield desired information. Thus, with the usual definition of the velocity in a turbulent flow as consisting of the mean and fluctuating component $u=\bar{u}+u'$, the mean velocity may be obtained from

$$\bar{u}=\frac{1}{n}\sum_{i=1}^{k}f_i u_i \tag{3}$$

where

$$n=\sum_{i=1}^{k}f_i$$

is the total number of observations, and f_i is the number of samples of the total number of observations having the velocity u_i.

From the mean velocity and the stored individual velocities the standard deviation may be obtained, which is nothing less than the turbulent intensity. Thus,

$$\sigma=\left[\frac{n\sum_{i=1}^{k}f_i u_i^2-\left(\sum_{i=1}^{k}f_i u_i\right)^2}{n(n-1)}\right]^{1/2}=\sqrt{\overline{u'^2}} \tag{4}$$

The last two equations indicate that the mean velocity and the turbulent intensity may be obtained easily using an LDV.

As indicated previously, the concentration of species and their temperature can be obtained instantaneously (10-15 ns) and simultaneously using the high-power short time duration laser pulse technique by means of the Raman effect. Defining the concentration and temperature data in analogy to the velocity $u=\bar{u}+u'$, as $C=\bar{C}+C'$ and $T=\bar{T}+T'$, it is possible to obtain the mean concentration and temperature, as well as the concentration and temperature fluctuation in the given flow. One has only to substitute the instantaneous concentration or temperature for the velocity u_i. In this procedure $\bar{u}$, $\bar{C}$, and $\bar{T}$ are defined as time averages at a point in space, with the understanding that the mean values are taken over a sufficiently long interval of time for them to

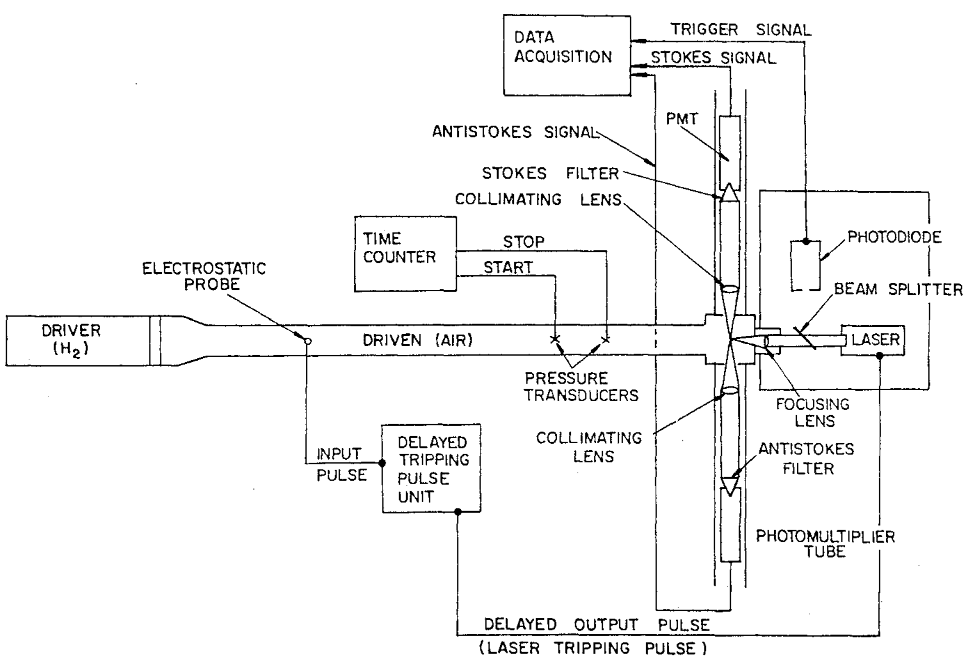

Fig. 2 Schematic of the shock tube experiment.

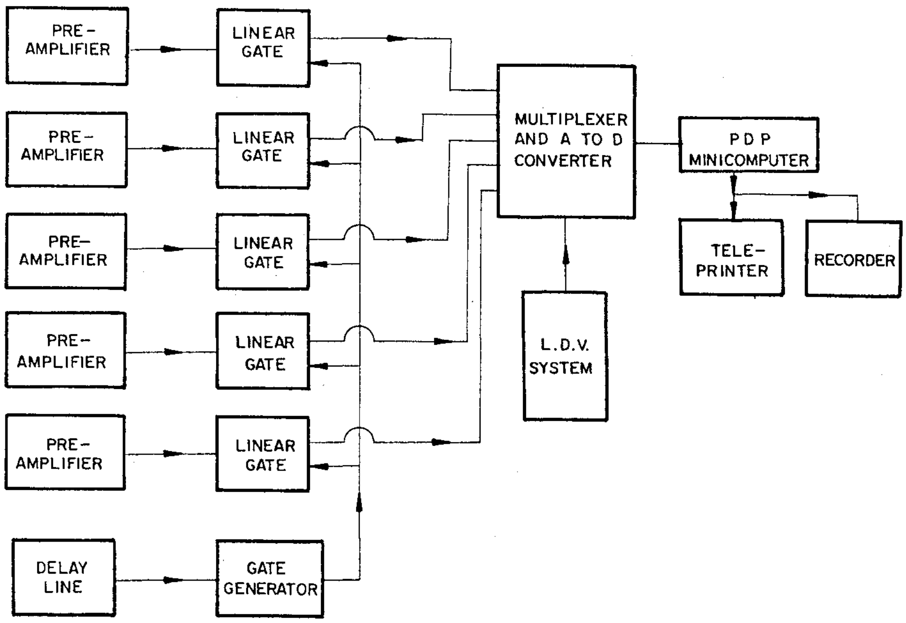

Fig. 3 Data acquisition system.

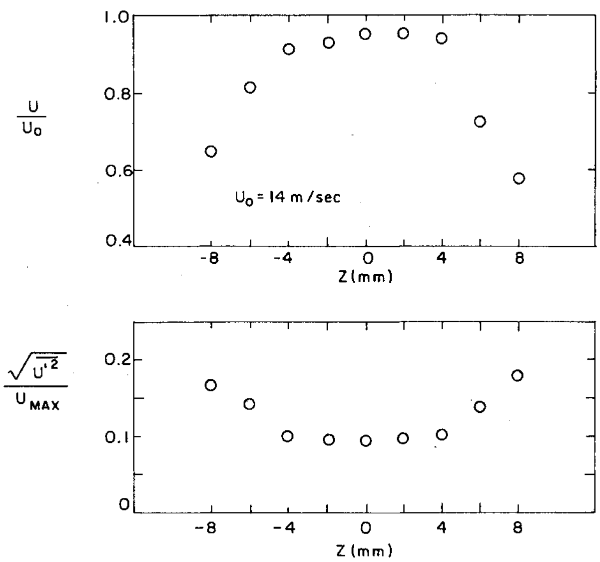

Fig. 4 Radial velocity and turbulent intensity profile at $X/D=5.8$ in an air methane flame.

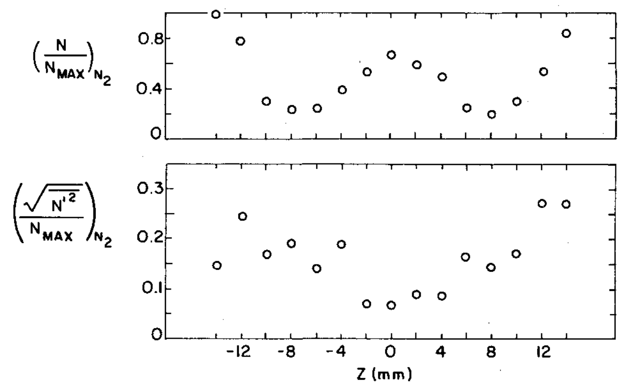

Fig. 5 N_2 concentration profile at $X/D=5.8$ in an air methane flame.

become completely independent of time. It has been shown in Refs. 11-13 that in chemically reacting flows "the effects of concentration fluctuations can be significant to the point of dominating the chemical reaction rates." It is pointed out that for a strongly skewed distribution of C_α and C_β in a two-specie reaction case, where the concentration fluctuations become dominant, the third-order correlations of these distributions must be included in the generalized chemical kinetic model. In the case of a turbulent chemically reacting flow, where the reaction rates are fast and the scale of turbulence is large, the reaction model based on mean value chemistry may be substantially in error. It is therefore necessary in chemically active turbulent flows to include second- and higher-order correlations involving the concentration fluctuations. These, as defined by Hilst et al.[11] are

$$\overline{C_\alpha' C_\beta'} = \frac{1}{N} \sum_i n_i (C_{\alpha i} - \overline{C}_\alpha)(C_{\beta i} - \overline{C}_\beta) \qquad (5)$$

where n_i is the frequency of occurrence of the joint values of $C_{\alpha i}$, $C_{\beta i}$; $N = \Sigma_i n_i$ and C_α and C_β are the concentration of species α and β:

$$\overline{C_\alpha'^2 C_\beta'} = \frac{1}{N} \sum_i n_i (C_{\alpha i} - \overline{C}_\alpha)^2 (C_{\beta i} - \overline{C}_\beta) \qquad (6)$$

and

$$\overline{C_\alpha' C_\beta'^2} = \frac{1}{N} \sum n_i (C_{\alpha i} - \overline{C}_\alpha)(C_{\beta i} - \overline{C}_\beta)^2 \qquad (7)$$

Since the spontaneous Raman effect used as indicated previously is capable of providing the concentrations and temperatures of a number of species in a mixture simultaneously, a simple processing procedure according to Eqs. (5-7) would provide the desired parameters.

With all of the basic data stored in the data acquisition memory system, it is quite simple to construct a number of correlations of interest, for example, a correlation between the velocity and concentration, velocity and temperature or temperature and concentration, etc.

It is obvious from the foregoing that the spontaneous Raman diagnostic techniques are quite unique, in that they can provide nonintrusively a wealth of information, not easily otherwise obtainable. One's enthusiasm concerning these techniques must, however, be tempered by the realization that there are limits of applicability of the spontaneous Raman technique. Those limits are, in many cases, imposed by the low achievable signal-to-noise ratio, which can be traced to the low equivalent Raman scattering cross sections, and by

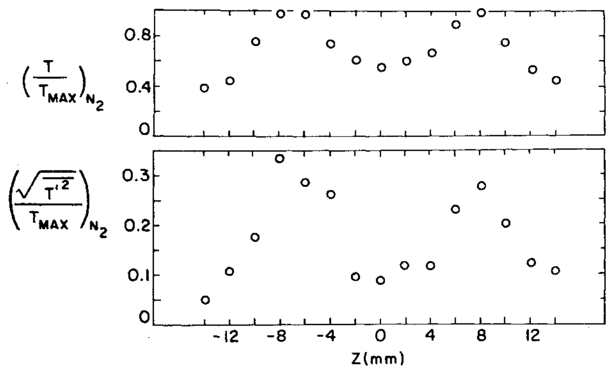

Fig. 6 N_2 temperature profile at $X/D=5.8$ in an air methane flame.

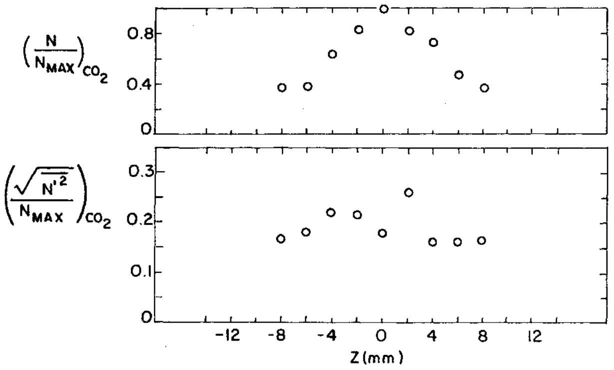

Fig. 7 CO_2 concentration profile at $X/D=5.8$.

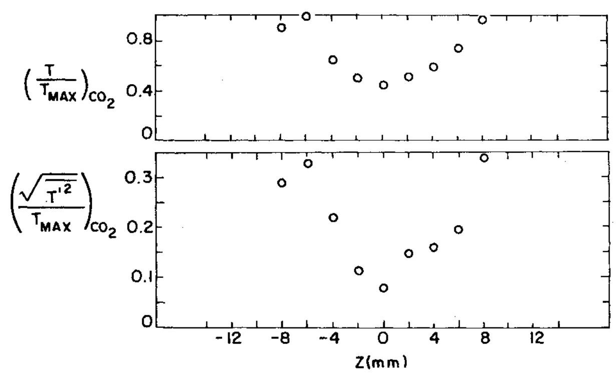

Fig. 8 CO_2 temperature profile at $X/D=5.8$.

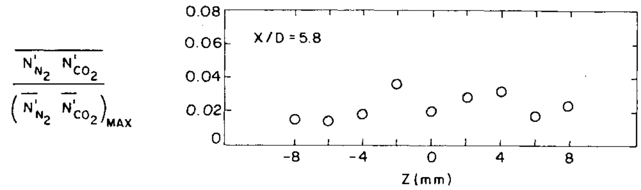

Fig. 9 N_2-CO_2 concentration crosscorrelation, radial profile in a flame.

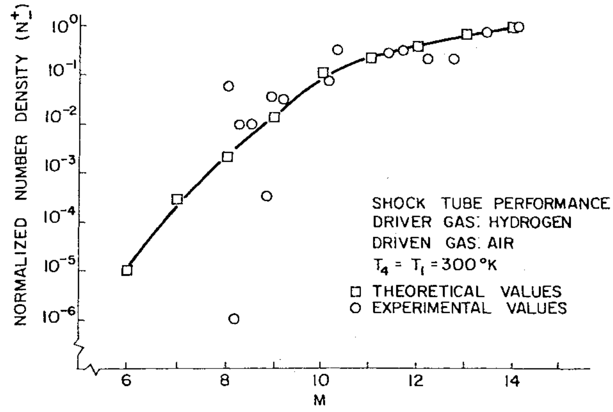

Fig. 10 Normalized N_2^+ number density.

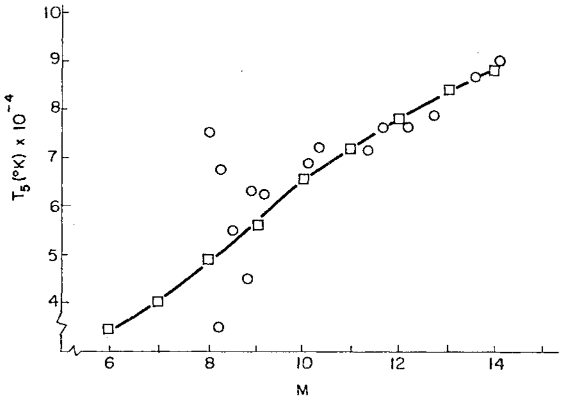

Fig. 11 Temperature behind the reflected shock.

attempted measurements in excessively hostile environments. The combination of a very noisy environment, low scattering cross section, and a low concentration of the specie of interest may render a particular measurement useless. It is therefore of utmost importance to evaluate the system in terms of the possibly achievable signal-to-noise ratio. In most cases it is possible to optimize the system, be it by higher-energy shorter duration laser pulses, narrower bandpass filters, or higher-resolution spectrographs and properly gated data acquisition electronics.

Experimental Apparatus

The experimental apparatus utilized in this work is shown diagramatically in Figs. 1 and 2. The apparatus of Fig. 1 consists essentially of a 3-J Q-switched ruby laser capable of delivering 5 pulses per minute of 20 ns in half-width corresponding to approximately 150 MW/pulse. Four receiving stations focused at the same point, each equipped with a photomultiplier placed in a thermoelectric cooler, can provide Raman signals corresponding to the species at their focal points. The type of information depending on the interchangeable narrow bandpass filters placed in the collimated portion of the collected scattered beam. For the experiment at hand, the receivers were equipped with bandpass filters corresponding to Stokes and anti-Stokes vibrational lines of N_2 and CO_2. This system enables the apparatus to provide concentration and temperature data concerning both of these species simultaneously. The apparatus included also a one-dimensional LDV system which was providing velocity information. Both the Raman and LDV systems were focused at the same point. The jet or flame mounted on an adjustable base could be moved in three directions, thus permitting the determination of radial and axial profiles, while the laser and optical systems remained in a fixed position. The outputs of the photomultipliers of the Raman and LDV systems were fed into appropriate processing electronics and an on-line computer. After each series of tests the total number of stored data were processed and printed out according to a preprogrammed format. It should be noted here that the jet was of coaxial construction. Air, CO_2, and the LDV scattering particles were fed through the center and methane through the outer portion of the coaxial jet system.

The apparatus of Fig. 2 present a schematic diagram of an experiment where the temperature and concentration of an ionized specie behind a reflected shock in a shock tube are measured. As is clear from the figure, a ruby laser pulse is incident at the reflected shock in the shock tube, and the stokes and antistokes radiation of an ionized specie is measured at 90 deg to the incident radiation. Here a 1-J ruby laser is utilized in combination with proper synchronization and measuring photomultiplier tubes. Figure 3 is the block diagram of the data acquisition system common to all experiments. The data are fed to the data acquisition system, where they are processed, reduced, and presented in the appropriate form. The signals from the photomultiplier tubes are routed through preamplifiers to linear gates, mutliplexer, and through an analog-to-digital converter to a storage and computing facility. The heart of the system is the linear gate. It is an integrating amplifying and stretching module actuated by a trigger signal which opens the gate for a predetermined period of time coincidental with the arrival of the Raman signal. By synchronizing the opening of the gate with the arrival of the signal and closing the gate at the end of the signal, which in the case of the Q-switched ruby laser is only 10 to 20-ns long, a better signal-to-noise ratio is possible particularly in a hostile environment where ambient radiation may be significant.

Experimental Results

With the apparatus described, a series of tests have been conducted. The purpose of these tests was the demonstration of the applicability of the integrated Raman-LDV system and the presentation of some turbulence related data obtainable from the pulsed Raman system, as well as the ability to obtain some correlation data. Thus, Figs. 4-8 present a typical series of profiles at $X/D=4.5$.

The group consists of a velocity profile and the corresponding turbulent intensity normalized to the maximum velocity, N_2 concentration and the corresponding N_2 fluctuation, temperature profile based on the N_2 stokes to antistokes intensity ratio and the corresponding temperature fluctuation, CO_2 concentration profile and its fluctuation, and, finally, the temperature and temperature fluctuation profile based on the stokes to antistokes intensity of CO_2 in the flame. Figure 9 represents the mixedness parameter or crosscorrelation parameter corresponding to the N_2 and CO_2 concentration profiles of the preceding group.

It is worth pointing out here that while the velocity and the corresponding turbulence intensity profiles of the data presented were based on a histogram of 2000 points/point, the N_2, CO_2, and temperature radial profiles were based on a histogram of only 50 points/point, and the corresponding axial profiles on histograms of only 30 points/point. This circumstance by itself may be sufficient to cause some higher than expected fluctuations. It is obvious that for a reasonable statistical sample a higher number of points per point is desirable. Thirty or even 50 points/point cannot be considered sufficient.

Finally, using the apparatus of Fig. 2 and the spontaneous Raman effect, the concentration and temperature of ionized nitrogen have been measured behind the reflected shock, in hydrogen driven air. The results are shown in Figs. 10 and 11, where the $N_2{}^+$ specie concentration normalized to the ion number density at Mach 14 and the temperature of $N_2{}^+$ behind the reflected shock are shown, respectively. The temperature was obtained from the ratio of the Stokes to the anti-Stokes Raman intensity measured simultaneously.

It should be noted that at low shock Mach numbers in the range of 8 to 9, the scatter is unacceptably high. This can be attributed to the low concentration of ion species and consequently, the signal-to-noise ratio was of the order of 1, and therefore no reliable data could be expected. As the shock Mach number increases, the concentration of the measured ionized specie increased, the signal-to-noise ratio increased, and as can be seen, the measured concentration as well as the temperature agree closely with the theoretically predictable values.

Conclusion

The work presented here through the combined use of laser Raman scattering and laser Doppler velocimetry has achieved the long sought after simultaneous, nonintrusive, instantaneous, and pointwise measurements of many thermodynamic and fluid flow variable, as well as correlation parameters. With this wealth of information, further correlations can now be determined and other thermodynamic properties inferred. Furthermore, it has been demonstrated that the spontaneous Raman effect is capable of providing information concerning ionized specie concentration in a plasma as well as their temperature. This may be of major importance in the characterization of MHD flows, particularly since this technique is pointwise remote and nonintrusive. It is believed that these laser-based diagnostic techniques may lead to a better understanding of the turbulent phenomena and in particular the complicated reacting turbulent fluid flow problems. There are, of course, limits to the applicability of the spontaneous Raman diagnostic techniques such as low scattering cross section and low signal-to-noise ratios in hostile environmments, etc.; but in comparison with other measuring techniques, the information obtainable justifies putting up with some of the difficulties.

It is evident from the experimental data presented in this work that the spontaneous Raman scattering diagnostic technique is particularly suited for the experimental determination of some of the correlation parameters, which may be of importance in modeling of turbulent, turbulent chemically reacting flows, and turbulent MHD flows.

Acknowledgment

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