# LASER DIAGNOSTIC TECHNIQUES FOR FOSSIL FUEL FLAMES

Patrick Hughes - Energy, Mines and Resources Canada

## Introduction

Since the advent of the laser the combustion scientist has had at his disposal a very powerful tool for extractng unbiased information out of the flame. Up until that time it was necessary to insert a cooled probe into the flame and extract the necessary information. More often than not the mere act of taking a measurement with an intrusive probe causes an error in the measurement. There have been attempts to estimate the error or develope a correction factor for intrusive probes; however, the ultimate technique would be to take the measurement without disturbing the measurement environment. This is possible using laser technology.

## Description

### Temperature and Species Concentration

Of the variety of optical techniques available to measure temperature or species concentration, the coherent anti-Stokes Raman spectroscopy (CARS) technique is shown to be the most applicable to combustion studies. The two most important advantages of the CARS technique are that it has very good signal to noise characteristics and that it gives good spatial and temporal resolution. The latter is of particular interest for turbulent environments. A spatial resolution of 100 μm by 0.5 cm is easily attainable and because pulsed lasers are used, a temporal resolution of 10 ns is possible.

The set-up is shown schematically in Figure 1. The optical arrangement is typical of a broadband CARS experiment. The source is a doubled Nd-YAG laser operating at 10 Hz to 20 Hz. Part of the doubled YAG beam is used to drive a dye cell oscillator - amplifier configuration (the two DC's Figure 1). The remainder of the YAG beam is split into two beams (BS and M) to act as the pump beam ($\omega_1$) for the generation of the CARS beam. The laser beam generated in the dye laser functions as the stokes beam ($\omega_s$). Where these three beams mix in the flame (at the focal point of lens FL), a fourth coherent beam is generated. Spectrally this beam is situated on the anti-Stokes side of the pump beam and results from a Raman active transition of the molecule under interest. It is for this reason that the technique is termed coherent anti-Stokes Raman spectroscopy. After the recollimating lens (RL) the pump and stokes beams are stopped at the trap (T) and the CARS signal is directed to the spectrograph either by mirrors as shown in Figure 1 or by a fiber optic link. The CARS beam is dispersed in the spectrograph onto an optical multichannel detector (OMD). The dispersed signal is then digitized and sent to a computer for analysis. A small fraction of the CARS signal is split off and directed onto a photomultiplier tube (PMT). This is used as an alignment aid.

---

[1]Hall, R. J., Eckbreh, A.C. "Coherent Anti-Stokes Raman Spectroscopy (CARS): Application to Combustion Diagnostics" to appear in "Laser Applications (Vol V) Figure 5, by permission of the authors.

## Flow Visualization

The ability to see phenomena in combusting environments can help in understanding the mechanisms involved in combustion. The mixing phenomenon and the structure of turbulent eddies are just two of the many physical phenomena of interest when studying the behaviour of flames. The schlieren technique is the most used to perform these visualization experiments in flames.

The optical arrangement for the schlieren experiments is shown in Figure 2. The problems with laser schlieren experiments mentioned by Oppenheim et al[2] will be overcome by using a prism wedge filter arrangement as suggested by Oppenheim[2]. This prism wedge is inserted at the focal point of the second lens, in place of the knife edge (at the location of the marking aperture Figure 2). This prism should be of birefringent material with its optic axis parallel to the optic axis of the experiment. If polarized laser light is used then as the focal spot is moved to thicker (or thinner) regions of the prism, the plane of polarization of the exiting beam will be uniformly rotated. If the beam leaving the prism were passed through a polarizing filter then the intensity of the light leaving the filter would span the range of full extinction to full transmission. The amount of extinction depends on the location of the focal spot on the prism (i.e. on the thickness traversed through the prism).

As with all schlieren systems the marking aperture is adjusted to give an illumination on the image plane midway between full extinction and full transmission. A disturbance in the test section in the form of a refractive index gradient will cause a ray or a bundle of rays to be deflected. These rays will then pass through the prism at a location other than that in the undisturbed case. This will then result in the plane of polarization being rotated to a different angle than that of the undisturbed case. Therefore, a brighter or darker region will be written on the image plane.

A collection of these bright and dark regions, once recorded on film, look exactly like the image obtained from a white light knife edge schlieren system. There are two advantages a laser source has over a white light source in a schlieren system. First, because the laser source is so intense, phenomena here to fore too small to be studied by white light sources can be enlarged. Second, since the laser is truly monochromatic, the background illumination coming from the flame can be eliminated by using interference filters. In this way the photographs taken with a laser light source are of much better quality.

---

[2]Oppenheim, A. K., Urtiew, P. A., Weinberg, F. J. "On the Use of Laser Light Sources in Schlieren - Interferometer Systems". Proc Roy Soc A, Vol 291; 279-290; 1966.

## Discussion

The equipment purchased for these experiments is still going through the commissioning tests and so this discussion will be confined to its future use.

### Temperature and Species Concentration

The broadband BOXCARS arrangement shown in Figure 1 can be used to measure gas temperature and species concentration. The difference lies in the frequency of the Stokes beam ($\omega_s$) since the pump frequency ($\omega_1$) remains constant. The dye in the dye cell is adjusted such that the frequency difference $\omega_1 - \omega_s$ is equal to the frequency of a Raman active mode of the molecule under investigation. In air breathing combustion the nitrogen molecule is used for temperature measurements.

Using the CARS technique, flame temperatures can be determined to within 50K. The standard products of hydrocarbon combustion can be detected along with a variety of pollutants such as $NO_x$ and $SO_x$. Depending on the size of the molecule, concentration measurements can be made at a level of a few tenths of a percent; however, $H_2$ has been detected to below 100 ppm (0.01%)[3]. The technique for determining the gas temperature or concentration of a molecule in a flame is basically the same. A measured CARS spectrum is compared to that resulting from a theoretical calculation whose only parameter is either temperature or concentration. The temperature on concentration is adjusted in the theoretical calculation until the comparison between the theoretical spectrum and that from the experiment meets some "best fit" criteria.

The test-bed for the CARS technique in coal flames will be the Controlled Mixing Combustion History (CMCH) furnace. The conditions in a coal flame are simulated in this furnace; however, the coal combustion occurs in much more controlled environment and the optical paths are shorter. The CARS arrangement will be used to map the temperatue field in the furnace and study the coal devolatilization and combustion mechanisms. It is intended to "harden" the optical set-up for use in a research tunnel furnace. This furnace more closely simulates the industrial or utility application for coal flames. The CARS measurements in the tunnel furnace will be used to study the effects of burner aerodynamics and fuel type on combustion performance and pollutant formation.

---

[3]Regnier, P. R., Taran, J. P. E. "On the Possibility of Measuring Gas Concentrations by Stimulated Anti-Stokes Scattering". Appl. Phys. Lett. Vol 23; 240-424; 1973.

Flow Visulization

The laser schlieren set-up shown in Figure 2 consists of a 2W Argon Ion laser operating in the single line mode. The marking aperture is a birefringent prism and polarizing filter as described above. Depending on the background illumination from the flame, an interference filter may or may not be used before the recording medium. Both high speed, still and cine photography will be used to record the schlieren images.

The flow visualization techniques will be used in the CMCH furnace to study the devolatilization mechanisms of the coal. By enlargng the schlieren field around the individual coal particles, the location of the flame front in the evolving gases can be visualized. A technique using single beam interferemetry may be used to take measurements in the flame front. These visualization experiments will give a better understanding of the mechanisms involved in the combustion of coal.

The schlieren technique will also be used in the research tunnel furnace to study the aerodynamics and mixing processes in industrial burners. By using high speed cine photographic techniques the phenomena involved in the combustion of swirling flames can be studied. The visualization techniques can be coupled with the CARS measurements to give a better understanding of the processes involved in swirling, combusting flow and pollutant formation. The enlarging techniques described above can be used to study small scale phenomena such as flame stretch around coal particles.

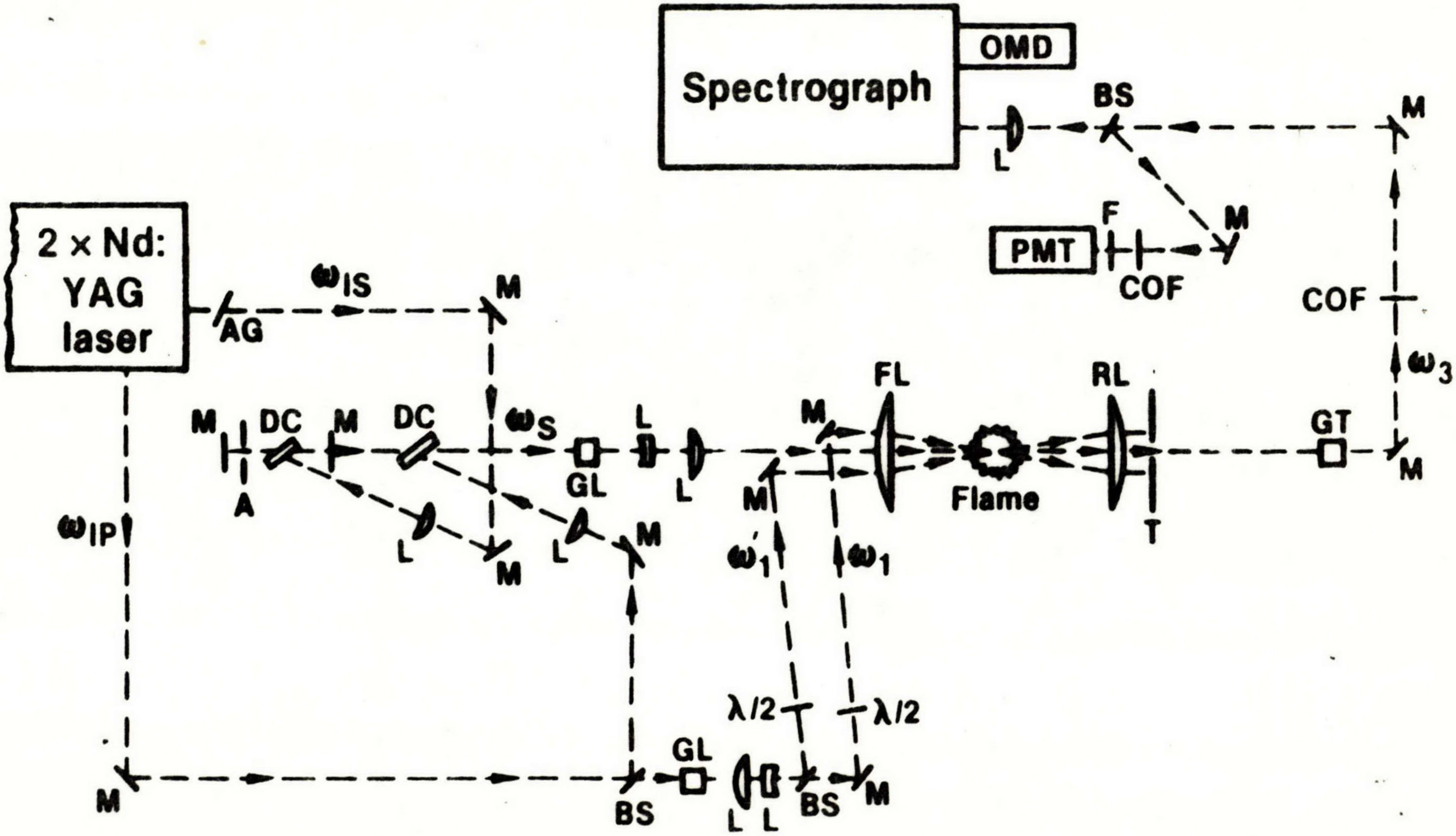


Figure 1 - The Optical Arrangement for a Coherent Anti-Stokes Raman Scattering Experiment

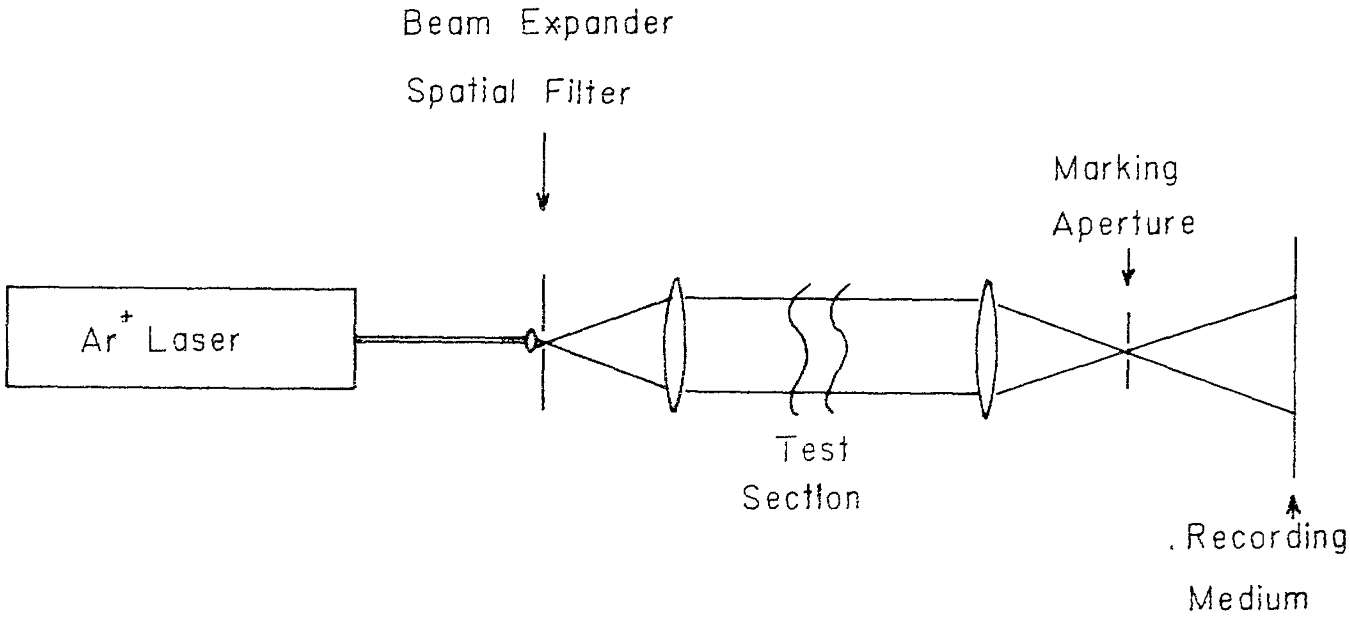


Figure 2 - The Optical Arrangement for a Laser Schlieren Experiment