EXPERIMENTS IN COMBUSTION
Lecture 2
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In Lecture 1, we first provided a description of the mixing and reaction process in two-dimensional turbulent mixing layers. We then proceeded to describe some measurements of the temperature and velocity field in a turbulent jet diffusion flame. In this lecture we continue with the subject of mixing and burning in round turbulent jets. We will proceed from various visualizations of jet flames to the application of planar laser techniques to gain a deeper understanding of the temperature field in jets. Of primary interest is the use of Planar Laser Induced Fluorescence and Planar Laser Rayleigh Scattering. Spontaneous Raman scattering, popular for point measurements, and now extended to line measurements will be described as well. We shall first describe the techniques and then provide examples of each as we proceed.

1. Visualizations of Jet Flames

The most common techniques for visualizing flames have been shadowgraph/schlieren visualizations, direct flame photography and laser based visualization.

In the schlieren technique, a parallel beam of light is passed through a flowfield, brought to a focus, spatially filtered there, and then imaged onto a camera, Fig. 1(a) (Ben-Yakar, 2001). This results in the first derivative of the index of refraction, $\partial n/\partial x$ being recorded on the image plane. Since gas density, ρ, can be related to index of refraction via

$$n - 1 = \frac{\rho}{\rho_o}(n_o - 1)$$

where subscript *o* refers to a reference condition (Goldstein & Kuehn, 1996), and assuming a perfect gas at constant pressure ($\rho \sim 1/T$) then

$$\frac{\partial n}{\partial x} \sim \frac{\partial \rho}{\partial x} \sim -\frac{1}{T^2}\frac{\partial T}{\partial x}$$

so there is a strong weighting to the lowest temperature regions in terms of beam deflection. Figure 1(b) shows a low-Re hydrogen jet flame, Re = 3,016, when viewed using the schlieren technique (Takeno, 1994). Note that the flame is dominated by smaller scales which are fairly random in appearance which is a result of the spatially integrating nature of the technique so that large-scale as well as small-scale features are both defined. Furthermore, on a cautionary note, the schlieren technique uses a spatial filter at the focal spot, which is usually a knife-edge, so different choices of spatial filter leads to quite different appearances of the same flow with several examples in Fig. 1(c) from Ben-Yakar (2001) for a supersonic, non-reacting jet of $Re > 10^5$.

An alternate approach is the use of direct flame photography as shown in Fig. 26 of Lecture 1 where several independent images of a propane flame are show. These images are of the entire flame brush so the lack of resolution hides details of the flame surface that are not immediately apparent. Alternately, one may use a fuel of higher sooting tendency such as ethylene, and by carefully selecting the camera exposure time, provide detailed images of the convoluted flame surface that constitutes the flame. Clear examples of this are shown in Fig. 2 from Muñiz & Mungal (2001) where soot emission from coflowing ethylene flames at *Re* = 8,200, 15,600 and 24,200 are shown as an indicator of the flame surface topology. The field of view is from 85 to 160 jet diameters downstream, and an exposure of 1/1000 sec is used to freeze the motion. Strictly speaking, soot exists on the rich side of the stoichiometric surface, but the ease of this technique provides a good sense of the complexity and distortion of the instantaneous flame surface as the *Re* increases.

A more recent technique to examine the flame sheet topology has been demonstrated by Schefer (1997). In this approach, CH chemiluminescence is used as a marker of the flame zone near the stoichiometric surface. The naturally emitted light is captured on an intensified CCD array fitted with an interference filter. The advantages are that no laser is required with this technique, it is straightforward to apply, and it requires only suitable collection optics and a sufficiently sensitive detector. The disadvantage is that it provides a line-of-sight measurement so that in highly turbulent flows where the flame sheet is significantly convoluted, interpretation of the flame sheet structure is difficult. Figure 3 shows an example of the application of the technique to a methane jet flame at a jet exit *Re* of 7,000. In this case two intensified cameras were used to view adjoining downstream regions of the flame. An interference filter centered at 431nm (10 nm bandwidth) was placed in front of each camera to allow light from the (0,0) band of the $A^2\Delta - X^2\Pi$ system of CH to be detected. A 150 μs intensifier gating time was used for adequate signal to noise ratio, while still effectively freezing the motion of the flow. The figure shows the sheet-like, cylindrical nature of the flame surface over a field of view from 10 to 80 mm downstream and 80 to 150 mm downstream respectively on each camera (for reference, the jet diameter is 5.4 mm and the discharge velocity is 21 m/s). Several outward bulges are apparent in the sheet which remains mostly intact, but occasional holes (indicative of local quenching) are also apparent in the surface.

In an attempt to produce an interior view of the flame, Turns *et al*. (1989) have used laser sheet lighting to illuminate the naturally occurring soot thus producing an internal slice of the flow. Examples of this are shown in Fig. 4 for the case of propane fuel at jet exit Reynolds numbers of 10,000 and 20,000. The image is obtained by sweeping the 488 nm light from a 2.5W CW laser using a rotating mirror at a high speed while recording on a film camera equipped with a 10-nm laser line filter to reduce the intensity of non-scattered light. The effective exposure time, obtained by dividing the beam width by the beam sweep velocity, was 4 μs which was quite adequate to effectively freeze the fluid motion. The image shows the quasi-laminar appearance of the eddies in the flow. There are also two type of images in each photograph: distinct, narrow, dark regions resulting from the light scattered from the