EXPERIMENTS IN COMBUSTION
Lecture 4
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The previous lectures have dealt with measurements in reacting flows in which the scalar field and the velocity field have been presented, but where each has been measured separately in a given flow. In this lecture we will describe some of the recent measurements which have been based upon the *simultaneous* acquisition of velocity and scalars in flames. The velocity is generally obtained via PIV from particles seeded into the flow. The scalar has been based upon PLIF, since our earlier discussion has shown that Rayleigh scattering requires a clean environment owing to its elastic nature, and Raman scattering is fairly weak and thus not well suited to measurements over regions of any significant size. We will first describe the challenges faced in simultaneous techniques and then illustrate with a series of examples in which new insights are being provided by such approaches. A repeatable flame/vortex interaction was investigated by Mueller *et al*. (1996) using PIV and OH-PLIF. Simultaneous PLIF of biacetyl and PIV in a simple unsteady flame has been reported by Frank *et al*. (1996). Simultaneous PLIF of acetone and PIV at the base of a lifted has been reported by Su *et al*. (2000). Simultaneous OH-PLIF and PIV measurements in turbulent jet flames have been reported by Hasselbrink *et al*. (1998), Rehm & Clemens (1998), Maurey *et al*. (1998, 2000) and Hult *et al.* (2000). Simultaneous CH-PLIF and PIV measurements have been reported by Donbar *et al*. (2001), Watson *et al*. (1999, 2000, 2002, 2003), Han & Mungal (2000a,b, 2002) and Kothnur *et al*. (2002). The recent book by Kohse-Höinghaus & Jeffries (2002) also discusses several examples not covered here.

1. PLIF Imaging In The Presence Of Particles

We have previously discussed PLIF imaging and PIV imaging separately. In the simultaneous approach the two systems are arranged to interrogate the same regions of space. Our discussion here will follow the development of Hasselbrink *et al*. (1998) whose experimental arrangement is shown in Fig. 1. The setup is used to study burning jets in crossflow using OH as a flame marker. The OH is excited by pumping near 283 nm from a Nd:Yag pumped dye laser, with detection near 315 nm onto a gated, intensified CCD array. The PIV system uses 532nm excitation from a Nd:Yag system with detection by a high resolution CCD array. Essential elements are the experimental timing and optical filtering details as shown in Fig. 2. The PIV camera is equipped with a 532nm line interference filter which rejects all but the PIV laser wavelength. The OH camera is equipped with a Schott UG-11 filter and three cascaded Schott WG-305 filters which reject flame emission and elastic scattering from the particles at 283 nm. The OH camera gate is open for 200 ns during and after the arrival of the OH laser pulse to allow the OH camera to reject flame emmission and view only the OH fluorescence. The OH laser pulse arrives 3μsec after the first of two PIV laser pulses, and the second PIV pulse arrives another 110μsec later. Four issues are of concern in the OH imaging aspect of any experiment: interpretation of the images, rejection of elastic particle scattering, the magnitude of fluorescence from particle-scattered light, and the possibility of particle/flame interactions. These are now discussed.

The first important issue with OH imaging in turbulent flows is interpretation of the images. OH formation reactions are fast (~20 μs), but the recombination reactions which eliminate OH are slow (~ 1-5 ms). Hence OH tends to linger in high temperature zones and cannot be considered to be in chemical equilibrium in most turbulent flows. In the experiment of Hasselbrink *et al*. (1998), in the imaged region, the flow time τ_{flow} = 2 ms, so that a Damköhler number based on formation reaction rates is $Da_{form} \approx 100$, but based on recombination rates is $Da_{recomb} \approx 1$. Clearly, some care must be exercised in interpreting the OH images.

Another important experimental issue is that Mie scattering at the laser wavelength must be rejected by the OH imaging apparatus in the presence of PIV particles. The magnitude of the problem can be estimated by calculating the number of photons per pixel expected from OH and particle scattering. OH signal is estimated using the fluorescence equation for broad laser line excitation and linear fluorescence,

$$N_{p,OH} = \eta \frac{\Omega}{4\pi} \chi_{OH} n V_C f_1(T) \frac{A_{21}}{A_{21} + Q_{21}} B_{12} E_\nu$$

where $\eta\Omega/4\pi$ is the overall collection efficiency, χ_{OH} is the OH mole fraction, n the overall number density, V_c the collection volume represented by a pixel, $f_1(T)$ the fraction in the lower state, $A/(A+Q) \approx A/Q$ is the Stern-Vollmer factor or fluorescence yield, B (cm^2/J-s) is the transition probability, and E_ν is the spectral fluence of the laser, i.e., the spatial intensity divided by the laser bandwidth (J-Hz^{-1}/cm^2). Particle scattering signal can be estimated as

$$N_{p,part} = \eta \frac{\Omega}{4\pi} I Q_{sca} \pi a_p^2 n_{part} V_c / h\nu$$

where I is the laser sheet intensity, Q_{sca} is the particle scattering efficiency, a_p is the particle radius, n_{part} is the particle number density, V_c the collection volume of a single pixel, h is Planck's constant and ν the laser frequency. This formulation assumes that all the scattering from a particle falls on a single pixel - actual particle diameter on the CCD array is, in the diffraction limit, $d_t \approx 2.44\lambda(1+M)f\#$ for small particles, smaller than the 23 μm pixels of the current OH camera (here λ is the laser wavelength, M is the magnification and $f\#$ is the f-number of the lens). Typical Q_{sca} for small particles is near two, but may be calculated for small spheres using Mie's approximate formula

$$Q_{sca} = 2 - \frac{4}{\rho} \sin\rho + \frac{4}{\rho^2}(1 - \cos\rho)$$

where $\rho = 2x(m-1)$, $x = 2\pi a_p/\lambda$, and m is the ratio of particle to fluid index of refraction. This can also be strongly influenced by polarization for particles small compared to the