EXPERIMENTS IN COMBUSTION
Lecture 3
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The previous lectures have dealt with mixing and combustion in turbulent mixing layers and jets. The majority of the discussion thus far utilized experiments in which primarily the scalar field is reported via either: the fuel concentration, the product distribution or the temperature field. A small number of results concerned the velocity field which were highlighted through LDV measurements, which are single point by nature. In the present lecture we wish to devote the majority of the discussion to Particle Image Velocimetry (PIV) which has become very popular in flames. Again the technique is a field measurement approach, rather than a point measurement, so that in addition to the traditional mean and rms of velocity, one is able to compute the in-plane strain rates and the out of plane vorticity components. We will first describe the technique, some of the important issues in application to flames, and finally demonstrate with examples concerning heat release in flames, flame liftoff in jet flames in coflow and in jet flames in crossflow. We will discuss the recent developments of Cinema-PIV which produces movie sequences of PIV images and finally conclude with a sample of 3D-PIV measurements in lifted flames.

1. Particle Image Velocimetry

PIV has seen rapid development in the fluid mechanics community since the 1980's. In the 1990's the technique passed from non-reacting applications to reacting applications and has now been demonstrated as being uniquely capable of providing new insights into flames which were previously unattainable with LDV. A number of excellent review articles exist on the technique such as Lourenco *et al*. (1989), Adrian (1991), Grant (1997) and the book by Raffel *et al*. (1998). The technique is shown schematically in Fig. 1. This image shows the PIV setup used by Muñiz & Mungal (2001) for the study of jet diffusion flames in coflow. The jet and coflow are seeded with particles and two pulses from a laser source illuminate the flow in rapid succession. This image is captured on film or a CCD camera at right angles to the beam direction where subsequent processing using an autocorrelation technique (or crosscorrelation as described later) is able to extract the velocity field at multiple points throughout the flowfield.

Figure 2 illustrates the basis of the autocorrelation technique. The image is first divided into small subregions where an autocorrelation of the subregion is performed with itself leading to the autocorrelation function as shown in Fig. 2b. Figure 2c illustrates the formation of the central peak, while Figs. 2d,e illustrate the formation of the positive and negative displacement peaks, while Fig. 2f illustrates a noise peak. In reality, while the correlation may be performed directly in the spatial domain, it is more common to first compute the Fourier transform, then the squared modulus and finally the inverse Fourier transform to find the autocorrelation function. Peakfitting algorithms (usually Gaussian or Whittaker reconstruction) locate the off-axis peak to subpixel accuracy, Fig. 3, where the displacement distance from the origin is proportional to the average distance moved by the particles in the interrogation volume. Since there is a velocity ambiguity concerning the direction of the flow, a bias technique is often required such that a fixed image displacement (i.e. velocity) can be applied to the recorded image so that all recorded velocities are unidirectional. The bias velocity can then be removed in the final software processing step, thus eliminating the velocity ambiguity. In several of the experiments to be described below this has been accomplished by means of a spinning mirror which applies a lateral shift to the image. In a more recent and popular development, the two images are captured on separate frames of a single CCD camera. In this way, the first image is always known, so that a crosscorrelation is performed between subregions and no directional ambiguity exists; this approach will also be used in the images to be described below. An additional advantage of crosscorrelation is the absence of the central peak of the autocorrelation, which if sufficiently close to the displacement peaks, can lead to errors in the peak finding algorithms.

2. Uncertainty Analysis in PIV

While PIV has seen much development in non-reacting fluid flows, there are a set of unique problems which exist in reacting flows which are discussed here. These concern the choice of seed, ability to follow the flow, beamsteering, the influence of refractive index gradients and the effect of thermophoresis. We will discuss these items next.

2.1 Particle Lag

Since the PIV measurement technique inherently measures the Lagrangian velocities of fluid tracers, v, to infer the Eulerian fluid velocity, $u(x,t)$, it is important to determine how well the particles follow the fluid motion. In gaseous flows with relatively heavy solid particles, the equation of motion of a small spherical particle in a noninteracting-particle suspension reduces to

$$\frac{\pi d^3}{6}\rho_\mathrm{p}\dot{\boldsymbol{v}} = 3\pi\mu d_\mathrm{p}(\boldsymbol{u}-\boldsymbol{v}) \qquad (1)$$

where the particle diameter, density and acceleration are d_p, ρ_p and $\dot{\boldsymbol{v}}$, respectively, and μ is the molecular viscosity of the fluid. The left side of the equation represents the particle mass times acceleration while the right side is equal to the Stokes drag force. Neglecting other force terms is applicable when (u-v) is small, the flow is incompressible and the particles are larger than the mean free path of the gas. As the flow accelerates, the inertia of the particles causes a delay in their response. For accurate PIV measurements, the slip velocity, (u-v), should be very small compared to u. Another way of characterizing particle-dynamic effects is to examine the Stokes number,

$$St = \frac{\tau_\mathrm{p}}{\tau_\mathrm{f}}$$