Simultaneous Scaler/Velocity Field Measurements in Turbulent Gas-Phase Flows

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In studying both nonreacting flows and flames it is useful to combine various imaging techniques to gain information that is not available from either instantaneous or time-averaged point measurements. The present work demonstrates a technique for combining particle-image velocimetry with planar laser-induced fluorescence in both a seeded air jet and a premixed flame. The results, which provide instantaneous images of both scalar and velocity fields, can be used to measure velocity distributions relative to contours in the scalar image. Of particular interest in the flame experiments is the ability to observe variations in the velocity field relative to contours of fuel concentration. In addition, the location of measured velocity vectors can be identified as being in either reactant or product regions of the flame. This capability permits the measurement of the mean and the fluctuations of both the product and reactant velocity fields.

INTRODUCTION

To better characterize turbulent gas-phase flows, a study has been undertaken to simultaneously measure the instantaneous scalar and velocity fields in two dimensions. The velocity field is obtained by particle-image velocimetry (PIV), while the scalar is measured via planar laser-induced fluorescence (PLIF) of biacetyl. Knowledge of both fields can reveal how the dynamics of the flow affect the behavior of a scalar, which in this case is the biacetyl concentration. Characterization of large-scale structures if of particular interest in the study of turbulent flows.

PIV has received much attention by researchers due to its ability to quantitatively measure instantaneous velocity fields. For general reviews of the method, see Refs. 1 and 2. The technique is based on recording a multiple exposure of a particle-seeded flow. By analyzing the image for particle displacements, two components of the velocity can be determined at multiple points within a plane intersecting the flow. Velocity field measurements are of particular interest in turbulent combustion systems because of the need to better understand interactions of flames and turbulence. PIV has been used to observe nonreacting flow patterns in motored engines [3, 4] and turbine components [5, 6]. However, implementing PIV in reacting flows presents challenges due to the large range of particle seeding densities brought about by the heat release. Some applications to combustion systems include internal combustion engines [7, 8], a propane diffusion flame [9], premixed propane/air flames [8, 10–12], flame-vortex interactions [13], and a coal flame [14].

The PIV technique described in this work uses a low-noise, high-resolution (2048 × 2048 pixels) charge-coupled-device (CCD) detector rather than photographic film to record particle images. The particle images from the detector are subsequently digitized and transferred to a computer for processing. The use of solid-state detectors for PIV, often referred to as digital particle-image velocimetry, has previously been demonstrated [12, 15–20]. Electronic data acquisition has the advantages of on-line optimization of experimental parameters and fully computerized processing of the PIV data. In relatively low-velocity flows, the framing rates of standard interlaced video cameras (25 and 30 Hz for PAL and RS-170 standards, respectively) permit the recording of a time sequence of particle images on sequential frames [15, 16, 19]. This approach resolves directional ambiguities and enables the measurement of zero velocities. Recently, it has been shown that the maximum velocities measurable with sequential video frames can be significantly increased by implementing appropriate electronic timing [12, 18].

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A significant drawback of standard video cameras is their limited spatial resolution and dynamic range. A larger format CCD enables more detailed velocity measurements in complex flows. Although more costly, high-resolution CCD cameras (1000 × 1000 pixels and larger) are available and have been incorporated into PIV systems [17]. However, detector readout times are substantially longer than those in video cameras. As a result, their application to PIV in most flows of practical interest requires that the multiple exposures of particle images be recorded onto a single frame. Therefore, each frame of data acquired from the detector represents a velocity field measurement that is independent of any previous frames. A further improvement in digital PIV can be gained from a low-noise, high-resolution, cooled CCD camera, as was used in this work. The larger dynamic range and greater sensitivity decreases the amount of particle-image dropout and reduces detector saturation problems. These characteristics allow more accurate PIV measurements to be performed in flows with large ranges of particle seeding densities, such as flames.

Laser-based methods for joint scalar/velocity measurements have been demonstrated in various combustion studies. Point measurements have combined laser Doppler velocimetry (LDV) with either spontaneous Raman [21–23], coherent anti-stokes Raman spectroscopy (CARS) [24], Lorenz-Mie scattering [25–30], or Rayleigh scattering [31, 32]. The Rayleigh/LDV technique requires temporal separation of the scalar and velocity measurements because the LDV seed particles interfere with the Rayleigh scattering. These techniques have yielded important information on velocity/scalar correlations in flames [30]. However, multidimensional measurements are necessary for studying effects such as strain and curvature. Previously, two-dimensional joint scalar/velocity experiments have been performed in flames by using the Lorenz–Mie scattering from particles for both PIV and number density measurements [8, 11, 13]. This combination of methods has provided important information such as effects of strain exerted by a vortex on a premixed flame [13].

In the present work, PIV is coupled with a molecular scattering technique, laser-induced fluorescence, to provide simultaneous velocity/concentration field measurements. This combination of techniques has recently been demonstrated for concentration flux measurements in a seeded water jet [33]. In that study, both the PLIF and PIV data were recorded on photographic film, rather than on an electronic detector, as was used in the present work. Although molecular scattering is a much weaker process than Lorenz–Mie scattering, it has the advantage that signal noise is not dominated by marker shot noise. In addition, the use of particles as a flow marker for gas concentration has inaccuracies resulting from the large disparity in the Schmidt Number of particles and gas molecules [34]. The resulting differential diffusion of particles and molecules is particularly important to consider when making measurements in nonpremixed flames. The mixing structures observed with particle tracers can differ significantly from those measured with molecular markers [35]. The demonstration of joint PIV/PLIF measurement in both a nonreacting jet and a premixed propane/biacetyl/air flame is reported here. Two different experimental configurations were used. A single laser technique was implemented in a nonreacting flow, and a two laser setup was used in a flame.

EXPERIMENTS

PIV/PLIF in a Nonreacting Jet

Ideally, the experimental configuration for simultaneous PIV/PLIF imaging requires only a single double-pulsed laser that both excites the fluorescing molecules and illuminates seed particles with two sequential pulses for PIV. The wavelength of the laser must fall within the absorption spectrum of the fluorescing molecule (approximately from 350 to 460 nm in the case of biacetyl) and provide enough energy to generate adequate fluorescence signal. The single laser experimental configuration shown in Fig. 1 was used for measurements in a nonreacting flow consisting of an air jet seeded with both biacetyl and submicron
sugar aerosols. The nonreacting jet was selected for an initial demonstration of simultaneous velocity/scalar field measurements in order to eliminate the additional complications of heat release and luminosity that are present in a flame. The third harmonic (λ = 355 nm) of a double-pulsed Nd:YAG laser (Quanta-Ray DCR-2A) was formed into a sheet to illuminate a 2-cm-high region of the flow. The interpulse time can be adjusted continuously from 25 to 200 μs to enable PIV measurements over a range of flow velocities.

Biacetyl (CH₃CO)₂ was chosen for the PLIF measurements because its fluorescence yield is relatively insensitive to variations in local composition and temperature (important in the case of the flame). In addition, the fluorescence signal is strong enough that two-dimensional laser sheet imaging is possible over a limited area. As a result, the recorded fluorescence intensity can provide measurements of relative biacetyl concentration. The use of biacetyl fluorescence for flow field visualization has been investigated in other studies [34, 36]. The blue fluorescence emission of biacetyl has a broad spectrum that peaks at approximately 470 nm and can be detected without cross-talk from the excitation wavelength. These features plus the nontoxicity of biacetyl make it useful for flow-field measurements. As a practical matter, biacetyl seeding concentrations can vary slowly over time, which makes it difficult to relate data from sequential images. In order to obtain absolute concentration measure-

ments, a calibration of biacetyl seeding density would be necessary on a shot-by-shot basis. A further complication occurs in a biacetyl seeded flame where variations in seeding density result in changes of the equivalence ratio. However, in the data presented here, the rms fluctuation in the seeding concentration was less than 4% and was indistinguishable from shot-to-shot fluctuations in the laser energy.

Submicron sugar aerosols were chosen as the seed particles for PIV measurements in the cold flow because of the relative ease of controlling their seeding density. The jet and a surrounding coflow were both seeded with these aerosols. Seeding of the jet was accomplished by passing a portion of the jet air through an aerosol generator (TSI Atomizer Model 9306). The remainder of the jet air was seeded with biacetyl vapor by bubbling it through a biacetyl bath. The separate air lines were then combined, and the jet issued through a 6-mm-diameter axisymmetric nozzle at an average exit velocity of 4 m/s giving Re = 1500. A wire mesh at the nozzle exit was used to introduce turbulent structures. The 50 mm diameter coflow was seeded only with sugar aerosols by passing the coflow air through a second aerosol generator (Sierra Instruments Model 7330).

For the PIV measurements, Lorenz-Mie scattering from the aerosols was imaged onto a CCD detector oriented normal to the laser sheet. The imaging optics consisted of two camera lenses that transmitted 355 nm light and an optical filter to block the biacetyl fluorescence. The cooled CCD detector (Photometrics KAF4200) was a 2048 × 2048 pixel array onto which a 1 × 1 cm² region of the flow was imaged. On the opposite side of the flow, a second cooled CCD detector (Photometrics Star 1) with an optically coupled single-stage image intensifier (ITT F4767P) was used to image the biacetyl fluorescence. This detector had a resolution of 384 × 576 pixels onto which a 1.5 × 2.2 cm² region of the flow was imaged. The fluorescence imaging optics included two camera lenses that did not transmit 355 nm light, eliminating cross-talk between the particle scattering and the fluorescence and making additional optical filters unnecessary.
Both the PIV and PLIF images were digitized and electronically transferred to a computer for storage and analysis. The PIV processing was performed on a laboratory computer using two-dimensional fast Fourier transform (FFT) techniques. Because the PIV and PLIF data were acquired with different detectors and collection optics, the proper scaling, cropping, and matching of the images had to be performed. The velocity field was then superimposed on the PLIF image. Figure 2 shows a sample of simultaneous velocity and fluorescence data obtained from a region centered 4.8 nozzle diameters downstream from the nozzle exit. The fluorescence signal level indicates the relative nozzle gas concentration. There is no directional ambiguity in the PIV measurements because all the vectors have a positive axial component.

A nonreacting flow was used here in the process of developing a diagnostic tool for flames. However, these scalar/velocity measurements could provide useful information in studying isothermal jet mixing. For example, both the conserved scalar and the velocity fields could be measured simultaneously since the distribution of a conserved scalar could be determined from the biacetyl concentration. Such measurements can give insight into the mixing structures of nonpremixed flames. One particularly interesting application is the study of the stabilization mechanism of lifted turbulent diffusion flames. Previously, images of fuel mole fraction have been used to determine the conserved scalar and the scalar dissipation fields in the nonreacting region upstream of a lifted turbulent methane diffusion flame [37]. The capability of joint scalar/velocity measurements could provide further insight into the stabilization mechanism of these flames.

**PIV/PLIF in a Propane/Biacetyl/Air Flame**

The experiments conducted in a premixed propane/biacetyl/air flame were performed using the experimental apparatus shown in Fig. 3. The configuration is similar to that described above. However, in this case separate lasers were used for the PIV and biacetyl fluorescence in order to improve the fluorescence signal. The absorption spectrum of biacetyl peaks near 440 nm and is relatively weak at 355 nm. Therefore, excitation of the PLIF with a flashlamp pumped dye laser (Candela LFDL-20) using Coumarin-440 dye provides an improved fluorescence signal. The second harmonic ($\lambda = 532$ nm) of the double-pulsed Nd:YAG laser was used for the PIV measurements. Both laser beams were overlapped with a dichroic beamsplitter and then formed into a single sheet to illuminate a planar region of the flow. The timing of the lasers was arranged such that the dye laser pulse occurred during the period between the two pulses from the Nd:YAG laser.

The flow used in this demonstration was an unsteady premixed propane/biacetyl/air flame stabilized on a 1.1-cm-diameter piloted axisymmetric burner (see Fig. 4). The average velocity at the burner exit was 4.8 m/s, giving $Re = 3500$. To enhance the turbulence, a perforated plate with 1-mm-diameter holes was placed inside the burner. Two separate air lines were used to seed the jet with biacetyl vapor and submicron alumina particles. Prior to exiting through the jet, both air lines were combined and mixed with propane. The equivalence ratio based only on the propane/air mixture was lean ($\phi = 0.6$). However, biacetyl is a hydro-
Fig. 2. A false color image of instantaneous nozzle gas concentration in an axisymmetric air jet seeded with biacetyl. The corresponding velocity field obtained from PIV measurements is superimposed.
Fig. 6. A false color image of reactant concentration measured with PLIF of biacetyl in a premixed propane/biacetyl/air flame. Velocity vectors from a simultaneous PIV measurement are overlaid.

Fig. 7. A high spatial resolution measurement of reactant concentration and velocity field in a premixed propane/biacetyl/air flame. The velocity field is plotted from a frame of reference convecting downstream at 4.8 m/s.
carbon fuel that is consumed in the flame, and its presence therefore increases the equivalence ratio. Biacetyl seeding density was limited by the biacetyl vapor pressure (∼ 40 torr at 20°C). To obtain an upper bound on the equivalence ratio, it was assumed that the air bubbling through the biacetyl bath was saturated with biacetyl vapor. The equivalence ratio computed using the total fuel (propane and biacetyl) was slightly rich (φ = 1.1). This overall equivalence ratio was consistent with the appearance of the flame. The 1.7-cm-diameter annular pilot consisted of a stoichiometric premixed propane/air flame that aided in anchoring the main flame to the burner. A refractory material was chosen for particle seeding so that the particles would survive the flame and allow velocity measurements to be performed on both sides of the flame front.

The detection scheme (see Fig. 3) was essentially the same as described above for the nonreacting flow. The PLIF signal was imaged onto the intensified CCD array with a spatial resolution of 0.04 × 0.04 mm². The single-stage image intensifier (DEP 1450DH) used in the fluorescence detection had a quantum efficiency 2.3 times greater than the intensifier used in the nonreacting flow experiments. Gating the intensifier for a 5-μs period bracketing the 3-μs dye laser pulse prevented any cross-talk from the PIV signal and minimized flame luminosity interference. In addition, an interference filter blocked background scattering and transmitted the broadband biacetyl fluorescence.

In two separate sets of experiments, imaging optics having different magnifications were used to collect the PIV data. The magnifications were 1.1 and 3.8, and the velocity measurements were performed over the regions indicated in Fig. 4 by areas A (14.9 × 13.9 mm²) and B (5.2 × 5.2 mm²), respectively. A narrow-bandpass (10-nm FWHM) filter centered at 532 nm reduced interference from flame luminosity, biacetyl fluorescence, and Lorenz–Mie scattering of the dye laser by seed particles.

RESULTS AND DISCUSSION

Low-Resolution Flame Measurements

An initial demonstration of joint scalar/velocity imaging in a flame was performed with relatively coarse spatial resolution in the velocity measurements. Therefore, the resulting measurements covered a large region of the flame. The ability to adjust the spatial resolution of the velocity field measurements is demonstrated below and is useful for studying flames on varying levels of detail. The coarse resolution measurements provide an overview of the flow field. Subsequent measurements at increased resolution can be used to zoom in on regions of particular interest.

A sample of the raw PIV data in which a single frame from the CCD camera contains pairs of particle images generated from the double-pulsed Nd:YAG laser is shown in Fig. 5. Superimposed on the particle image is a contour representing the approximate flame front location obtained from the corresponding biacetyl fluorescence image. (The method for calculating this contour is described in the following section.) The more densely seeded regions correspond to the unburned fuel–air mixture, while the sparser seeding is indicative of the presence of hot combustion products mixed with the unseeded ambient air. This image illustrates one of the challenges of performing PIV in a flame. The particle seeding density must be maintained at a level that
PIV processing based on scalar measurements has been further developed using the high resolution data described below.

High-Resolution Flame Measurements

In order to obtain more detailed information regarding the interactions of the flame and the flow field, higher spatial resolution measurements are necessary. To demonstrate this capability, the magnification (and hence resolution) of the PIV apparatus was increased as described above. In order to obtain valid PIV data, the seeding density was also increased. Figure 7 shows an image of biacetyl fluorescence intensity with the corresponding velocity field overlaid. A constant axial velocity of 4.8 m/s has been subtracted and the velocity vectors scaled to display details of the flow field as observed from a convecting frame of reference. The fluorescence image extends in the axial direction from 1.0 to 1.5 nozzle diameters downstream of the burner and in the radial direction 0.1 to 0.6 nozzle diameters from the jet axis. Each vector represents the average velocity over a $0.33 \times 0.33 \text{ mm}^2$ area. The separation between vectors is 0.165 mm. The acceleration of the product gases associated with the heat release near the flame front is evident.

The contour in Fig. 7 approximates the location of maximum velocity gradient in the reaction zone and was calculated from the PLIF measurement. This contour can be used to enhance the PIV processing (described below) and to provide an indication of the flame front position. There are a number of possible methods for estimating such a contour. Recent experimental and computational results in premixed methane/air counterflow flames provide some guidance. From the data of Law et al. [38], a comparison between the fuel mole fraction and normal velocity profiles indicates that the position of maximum velocity gradient approximately coincides with the location at which the fuel mole fraction equals 50% of its value in the initial mixture. This result appears to be relatively insensitive to variations in strain rate. However, other factors must be considered in the turbulent propane/biacetyl/air flame of the present work. For example, the

![Image](https://via.placeholder.com/150)

Fig. 5. A sample particle image used for PIV measurements in a flame. The contour plot, which was obtained from PLIF measurements, approximates the location of the flame front.
50% biacetyl signal level does not coincide with the location of maximum velocity gradient but is located on the fuel-rich side because of biacetyl pyrolysis.

The displacement between the maximum velocity gradient and the 50% biacetyl concentration was determined using a single pair of scalar/velocity images. The particular image pair chosen for this calculation had a 3.0 mm section of the flame front that was oriented parallel to the jet axis. Both the velocity and PLIF signals were averaged over this section. The average normal velocity component (U) and the average reactant concentration (Y) were then determined at various positions along the normal to the flame front. Both quantities were normalized using local maxima and minima such that, \( Y^\ast(x) = (Y(x) - Y_{\text{min}})/(Y_{\text{max}} - Y_{\text{min}}) \), and \( U^\ast(x) = (U(x) - U_{\text{min}})/(U_{\text{max}} - U_{\text{min}}) \), where \( x \) corresponds to distance along the normal to the flame front. Distributions of \( Y^\ast(x) \) and \( U^\ast(x) \) are plotted in Fig. 8. The velocity profile has been linearly interpolated between the locations of the PIV measurements. The distance of 0.3 mm from \( Y^\ast = 0.5 \) to \( U^\ast = 0.5 \) was identified as the displacement between the 50% biacetyl concentration and the maximum velocity gradient and was used as an offset in computing contours of maximum velocity gradient from biacetyl fluorescence images. It is noteworthy that the error in matching images from the two cameras was an order of magnitude smaller than this 0.3 mm offset. In addition, the width of the flame front, as determined from the velocity profile in Fig. 8, is on the order of 1 mm, which is consistent with the results of Law et al. [38] for a premixed methane/air flame.

Using the displacement value obtained from one image pair, contours of maximum velocity gradients were determined in the remainder of the data set by the following procedure. First, a fluorescence image was smoothed using 0.2 × 0.2 mm\(^2\) subdomains in order to reduce noise. Next, a contour was drawn at approximately the 50% signal level. This initial contour was then displaced away from the rich side along the direction normal to the contour by an offset of 0.3 mm. The displacement of the resulting contour can be seen in Fig. 7 where there is a gap between the fluorescence signal and the contour.

By using both the scalar and velocity fields, the locations of velocity vectors can be identified with either the reactant or the product regions of the flow. The mean reactant and mean product velocity fields were thus obtained from a data set containing 54 independent PIV measurements and are shown in Figs. 9a and 9b, respectively. Overlaid on these velocity fields are contours of the mean progress variable, \( \bar{\varepsilon} \), where \( \bar{\varepsilon} = 0 \) corresponds to the unburned state, and \( \bar{\varepsilon} = 1 \) represents the fully reacted state. \( \bar{\varepsilon} \) is computed by first transforming each fluorescence image into a binary image in which the level indicates the presence of either reactant or product [39]. The threshold level used to distinguish reactant from product is 50% of the fluorescence signal in the unburned fuel/air mixture at room temperature. The sum of 54 of these binary images, each derived from an independent fluorescence measurement, represents the spatial distribution of the mean progress variable. Because of the limited number of independent measurements, this image is then smoothed with a 0.39 × 0.39 mm\(^2\) subdomain. Contours of the resulting image correspond to approximate \( \bar{\varepsilon} \) contours. Instantaneous velocity fluctuations (Fig. 10) were obtained by subtracting the appropriate mean (reactant or product) velocity from the velocity measured at each point in the flow field. On the left of the contour is the reactant region where the swirling motion of a
Fig. 9. a. Mean reactant velocity field obtained from 54 independent PIV measurements. Contours of mean progress variable, $\bar{c} = 0.25, 0.50, 0.75$, are superimposed. 
b. Mean product velocity field obtained from 54 independent PIV measurements. Contours of mean progress variable, $\bar{c} = 0.25, 0.50, 0.75$, are superimposed.

Fig. 10. Instantaneous velocity fluctuation field with the approximate flame front contour overlaid.

large-scale structure has been resolved. Vectors in the product region, to the right of the contour, are significantly noisier than those in the reactant because of the reduced particle seeding density.

The PIV processing has been performed on a regular grid in which each vector was derived from a $128 \times 128$ pixel$^2$ subregion of the particle image. The presence of velocity gradients within a subregion can degrade the accuracy of the velocity measurement. In a flame, the effect of velocity gradients across the flame front are of particular concern. Keane and Adrian have used computer simulations of a PIV system to determine the detection probability of velocity vectors in a simple shear flow [40]. Using their predictions and the velocity gradients measured across the flame front, the detection probability for a subregion straddling the flame front was estimated to be greater than 90%. This result was consistent with the observed PIV results. However, to reduce the effects of spatial averaging of velocities near the flame front, the PIV processing has been modified to incorporate information from the scalar image. Subregions near the flame front can contain particles in both the product and reactant regions. In order to eliminate contri-
butions from both regions to the velocity vectors, a mask is formed based on the fluorescence image. If more than half of a given subregion's area falls on the reactant side of the flame front contour, the particle images in the product region are masked and set to a background level before the auto-correlation processing is performed. A sample of such a masked subregion is shown in Fig. 11. The resulting vector is designated as a reactant velocity. Although the number of particle images is reduced by masking, this approach can improve the accuracy of the velocity measurements in the flame front region where the largest velocity gradients are present.

Another means of using simultaneous scalar and velocity images is to measure the instantaneous velocity distribution along a contour obtained from the scalar image. To demonstrate this capability, the PIV processing has been modified to evaluate velocities along a reactant concentration contour obtained from a PLIF image. In order to automate this procedure, each 128 x 128 pixel$^2$ subregion is rotated such that one edge forms a chord along the contour. Subsequent subregions are separated by half the subregion dimension, 64 pixels, along the contour. Figure 12 shows a schematic diagram of the selection of subregions along a curve. This capability is of particular interest with respect to measuring statistics of the acceleration of gases in the direction normal to the flame front as well as the strain induced on the flame by variations of the velocity component parallel to the contour.

As a demonstration of this procedure, velocities were evaluated along a contour using one pair of PIV/PLIF images, and the results are displayed in Fig. 13. The contour was derived from the PLIF image, as was previously described. To the left side of the contour is the region containing unburned reactant. In Fig. 13a, the velocities, as measured in the laboratory frame of reference, are plotted on either side of the contour. Figure 13b, displays the velocity component normal to the contour. The axial component of the mean reactant velocity (4.8 m/s) has been subtracted to show the velocities measured with respect to a convecting frame of reference. The acceleration across the contour is the result of the heat release in the reaction zone. The measured acceleration depends in part on the orientation of the flame surface relative to the plane of the laser sheet. The normal velocity components are relatively noisy because the dominant displacement of the seed particles is in the axial direction while the normal component is generally more closely aligned with the radial direction. The result is that only a limited portion of the dynamic range of the PIV measurement has been used for the normal component. It should also be
noted that the convection velocities in this flow are an order of magnitude greater than the laminar flame speed. The total particle displacement is \( \sim 22 \) pixels while the displacement that corresponds to the laminar flame speed in only \( \sim 2 \) pixels. The precision of the velocity measurement is determined by the ability to locate the centroids of the correlation peaks. A conservative estimate is that these locations can be determined to within 0.5 pixels. This implies that for the velocity vectors typically measured in these flames, the precision is 2\% while the precision for the laminar flame speed is 25\%. However, on the product side of the flame front the normal velocity can be measured with a precision of 7\%. The precision of the normal velocity component may be improved by increasing the interpulse time and thus providing a larger particle displacement in the direction normal to the flame front. It may then become necessary to use a cross-correlation, or possibly an image shifting technique, in the PIV measurement. Figure 13c shows the fluctuation velocities on either side of the same contour. In computing the fluctuation velocities, the mean reactant velocities in Fig. 9a have been subtracted from the velocities on the unburned (left) side of the contour, while the mean product velocities in Fig. 9b were subtracted from the velocities on the burned (right) side of the contour. A large set of these measurements could provide a statistical analysis of fluctuations and acceleration near the flame front.

**SUMMARY AND CONCLUSIONS**

The combination of PIV and PLIF imaging techniques has been demonstrated in both a nonreacting gas-phase flow and a premixed flame using two different experimental configurations. The ability to simultaneously measure instantaneous scalar and velocity fields using CCD detectors can provide important flow visualization as well as statistical information on the interactions of the two fields. The considerable range of particle seeding densities in flames presents a challenge for performing

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Fig. 13. Instantaneous velocities evaluated along a contour from an instantaneous joint PIV/PLIF measurement. The region to the left of the contour corresponds to the unburned reactant region. (a) Velocities are shown relative to the laboratory reference frame. (b) A constant axial convection velocity of 4.8 m/s has been subtracted and the velocity component normal to the contour plotted. (c) Instantaneous fluctuation velocities are plotted on both sides of the contour.
PIV measurements. The large linear dynamic range and low readout noise of cooled CCD detectors prove advantageous to these measurements.

The simultaneous use of a tunable dye laser and a fixed wavelength double-pulsed solid-state laser for joint scalar/velocity field measurements broadens the possibilities for applications of this technique. A tunable laser can provide access to fluorescence measurements of a variety of species. Although laser-induced biacetyl fluorescence affords a strong signal, fluorescence imaging of radicals, such as CH or OH, could provide a more accurate marker of the flame front location for studying flame front interactions with the velocity field. However, using a vapor, such as biacetyl, as a scalar marker is an improvement over the use of solid particles, as have been used previously in PIV/scalar experiments.

The PIV/PLIF measurements in this work demonstrate the feasibility of obtaining detailed information on interactions of flames with turbulent flows. High spatial resolution was obtained in a premixed flame yielding a velocity field measurement with vector separations of 0.17 mm. Several possibilities for incorporating information extracted from scalar images into the PIV processing routine have been demonstrated. These include varying the processing resolution in the unburned and burned regions of the flame, masking techniques to improve velocity measurements near the flame front, and measuring velocities along a contour obtained from the scalar image. The potential applications of joint scalar/velocity field measurements to the study of combustion systems are quite extensive. This work demonstrates some of the capabilities that are possible with the use of electronic detectors and computerized processing.

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