Application of Gaseous Image Velocimetry to Laminar, Unsteady Flames

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Abstract

It is demonstrated in this work that velocity field measurements can be performed in laminar diffusion flames without particle seeding. This yields several advantages compared to particle-based techniques, such as LDV or PIV, as discussed in the text. In particular this technique can be combined with Rayleigh and Raman scattering, so that simultaneous temperature and species densities measurements can be done. The spatial resolution and accuracy of the new technique are discussed.

Introduction

The recently developed gaseous image velocimetry (GIV) technique is applied to laminar, unsteady flames for the first time. GIV is closely related to particle image velocimetry (PIV), but yields several advantages because it is not based on seed particles. Instead molecular tracers are used and double-pulse visualization is performed using laser-induced fluorescence (LIF). It was briefly demonstrated in a prior paper that GIV can in principle be applied to turbulent flames [1]. GIV has been validated for the first time by comparing it to PIV in a laminar, unsteady, *nonreacting* two-phase flow [2]. It is now necessary to investigate the capabilities and the accuracy of this method in more detail in flames under well controlled conditions. This is done in the present work by applying GIV to laminar, unsteady hydrogen diffusion flames. In the prior paper [1] it is shown that GIV can be combined with simultaneous Raman scattering, Rayleigh scattering, and additional LIF measurements. This can be employed for simultaneous spatially-resolved measurements of majority species densities, temperature, and minority species. In particular density-velocity correlations could be measured by combining GIV and Rayleigh scattering. Such correlations were measured previously by combination of laser doppler velocimetry (LDV) with Mie scattering or LDV with Rayleigh scattering, respectively, as reviewed by Ferrao and Heitor [3]. The limitations of these techniques based on particles are well known. For example, high concentrations of seed particles may disturb the flow field and/or chemistry. The particles may also lag behind the gas flow, and in addition sharp temperature gradients may cause large errors (up to 25 % in Ref. 4) due to thermophoresis. In contrast, GIV works without seed particles, so that Rayleigh scattering is not obscured by Mie scattering, and consequently GIV and Rayleigh measurements can be performed without any delay. It should also be noted that GIV yields instantaneous velocity fields in contrast to pointwise LDV. The first planar density-velocity correlation measurements in flames were presented recently based on double pulse Rayleigh scattering [5]. However, the velocity fields measured in this way may generally be affected by changes in the 2D Rayleigh scattering due to chemical reactions or other factors that change the signal intensities between the two laser pulses. In contrast, GIV is based on specific molecular tracers which are sufficiently stable in combustion, such as NO (or OH under certain conditions), so that changes in the 2D distribution of these tracers can be clearly attributed to fluid motion. Changes in the LIF signal due to temperature gradients can be suppressed by the proper choice of the LIF excitation line and by short delay between the two pulses [1], [6].

The data reduction scheme used in this work borrows from the image correlation velocimetry (ICV) method proposed by Tokumaru and Dimotakis [7]. A number of related methods for velocity determination from two consecutive images of a passive scalar are discussed in their paper. It should be emphasized that this algorithm, which is not based on cross-correlation analysis as most previous studies [5], yields much higher spatial resolution than cross-correlation analysis as demonstrated below.

A number of related velocity measurement techniques, that do not depend on particle seeding, are given in the literature: The technique described by Boedeker [8] is based on the photolysis of water vapor. Thus, it is only applicable in environments with sufficient water content. Doppler methods, e. g., the technique published by Paul et al. [9], are not very accurate in the low velocity range. Other approaches, which are based on oxygen or tracers, which burn in high-temperature media, generally cannot be applied \`across the reaction zone´ in combustion [10]- [13]. Also these tagging techniques, which are performed on lines or grids, generally do not yield countinuous data in two dimensions. In contrast, GIV is a 2-D continuous-field technique in the present state and can in principle be extended to three dimensions. It is noteworthy that GIV can also be combined with PIV, so that the velocities of gaseous and liquid phase can be measured simultaneously in sprays and aerosols [2].

Experimental

The set-up is schematically shown in Figure 1. A laminar, unsteady, axisymmetric diffusion flame is generated by modulating the fuel (hydrogen) stream discharged from a round orifice (inner diameter 6 mm) by using a loudspeaker. This approach is similar to the work presented by Lewis et al. [14]. As a first approach the tracer gas (NO) is seeded into the tube of the vortex ring generator using a pulsed valve as shown in Fig. 1. GIV depends on spatial gradients in the tracer gas distribution, which are exploited for tracing the velocity field. It is necessary to generate inhomogeneous tracer distributions a short time before they are probed, because gaseous tracers are susceptible to molecular diffusion. It is also desirable not to disturb the flow by the seeding process. Both is achieved in the present set-up by a special seeding method which is outlined in the time sequence in Figure 2: There is a small prechamber attached to the vortex ring generator through a number of holes (the loudspeaker is located underneath, i.e. upstream, the tube shown in Fig. 2). First a small amount of pure NO is discharged into the prechamber (labelled "B"). Then the speaker is triggered once to clear the tube ("C"). After that small portions of the remaining NO in the prechamber diffuse into the tube generating an NO pattern in the hydrogen stream ("D"). Then the speaker is triggered a second time ("E") and the measurements are performed in this second vortex bubble. This seeding method yields inhomogeneous NO distributions in the resulting flow field, which are exploited for GIV data evaluation. The GIV measurement system contains two tunable KrF excimer lasers and an intensified progressive scan CCD camera. The excimer lasers generate two consecutive laser pulses at 248nm. The radiation is shifted to 226nm by stimulated Raman scattering in order to excite NO via the $\gamma(0,0)$ band system. The measurement system is capable of recording two images with a delay down to 1μs.

Results and Discussion

Figure 3 depicts a velocity field (8 x 10 mm^2) that was measured 1.3 ms after triggering the speaker. A constant velocity of 44m/s (upwards) has been subtracted from all vectors in order to visualize the rotational motion: The toroidal vortex core can be clearly identified. The magnitude of the velocity vectors in the center of the image equals ~16m/s. The reaction zone, as determined from OH imaging (not shown), is located close to the outer edge of the velocity vectors shown in Fig. 3. A pair of corresponding LIF raw data images are shown underneath the vector plot. It can be seen that the NO distribution does not simply reflect the fluid discharged from the orifice, but there are modulations in the NO signal. They are caused by the seeding method described above. The GIV data evaluation depends on these gradients. It is clear that the magnitude of the gradients affects the spatial resolution of the method. Stronger gradients than in the raw images in Figure 3 can be achieved by improving the seeding process (unfortunately "holes" in the NO distribution tend to occur under this condition). A resulting single shot LIF image (9 x 10 mm^2) is shown as an example on the right hand side in Figure 4. It can be seen that there is a sequence of NO "blobs" within the left "branch" of the vortex bubble, which is wrapped up and drawn into the vortex core. The resulting instantaneous velocity field shown in Fig. 4 has a spatial resolution of 0.3 mm corresponding to the spacing of the vectors. It should be emphasized that this spatial resolution could not have been achieved by simple cross-correlation analysis, because the spatial resolution is much smaller than the typical length scale of the NO structures. The left side of the vortex core can be clearly seen in Fig. 4. The vorticity (z component) – defined as $(\nabla\otimes\mathbf{v})_z=(\partial_x v_y - \partial_y v_x)$ – of the vortex core is shown in the upper frame in Fig. 4. This demonstrates that this technique yields instantaneous, continuous velocity fields in such flames with a spatial resolution of 0.3 mm in the present state. The precision of the single shot data can be estimated – as a first approach – from the variability of a set of instantaneous velocity fields obtained under repeatable conditions. The standard deviation of the present instantaneous data equals ~10%. This variability includes shot-to-shot fluctuations in the flow field, which can be estimated from the fluctuations in the LIF raw data to be ~7%. Thus, the precision of the instantaneous GIV data is roughly ~7% (since $0.10^2 \sim 0.07^2 + 0{,}07^2$).

The OH radical can also be used as the flow tracer under certain conditions as proposed previously [15]. OH is very attractive because velocity profiles could be measured close to the reaction zone in *unseeded* flames. However, the limited lifetime of the OH radical must be considered. It is generally desirable to acquire two OH images with a delay that is short compared to the chemical reactions, so that changes in the OH distribution are solely caused by fluid motion. OH is formed via fast two-body reactions within ~15μs and recombines via slow three-body reactions within ~3 ms, respectively, in hydrogen-air diffusion flames [6]. This implies that the change in the measured OH distribution due to chemical reactions will be small if the delay of the two measurements is much smaller than 15μs. It is demonstrated in the following that the application of the GIV algorithm to double pulse OH images yields velocity profiles with high spatial resolution for the first time. A second set-up is used for this purpose: A laminar hydrogen-air diffusion flame is used similar to the set-up discussed above, but the flame is disturbed by a pulsed air jet that is directed towards the reaction zone from the air side. Figure 5 shows a pair of double pulse OH images measured with a delay of 5µs. The air jet is indicated by the large arrow. It can be seen that the jet penetrates the reaction zone under right angle. The velocity field depicted in Figure 6 was calculated from the OH images in Fig. 5 within the rectangle shown in the left frame. The magnitude of the largest vectors correspond to ~10m/s. It should be noted that the spatial resolution of this instantaneous velocity field equals 0.4mm as indicated by the spacing of the velocity vectors in Fig. 6.

Conclusions

It is demonstrated that instantaneous velocity field measurements can be performed in laminar, unsteady hydrogen-air diffusion flames based on double pulse imaging of LIF from NO or OH. The spatial resolution of the instantaneous velocity fields is determined to be 0.3 mm (NO) or 0.4mm (OH), respectivley, in the present examples. The precision of the instantaneous velocity fields based on NO is determined to be ~7% (relative error). This can be used for density-velocity correlation measurements in combustion, because it is possible to combine GIV with Raman and Rayleigh scattering as demonstrated previously [1].

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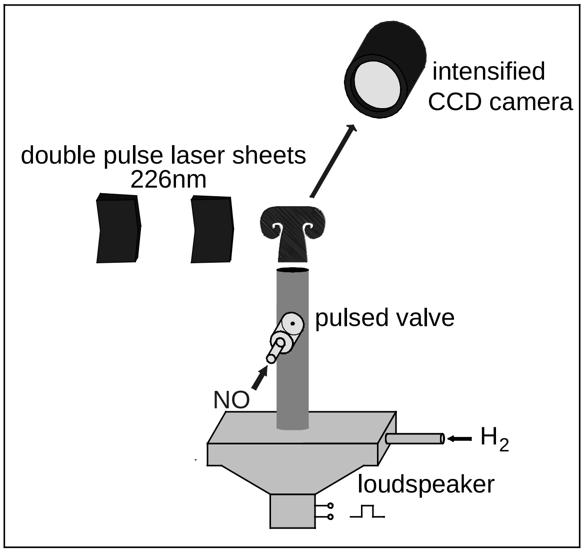

Figure 1: Experimental set-up (no. one)

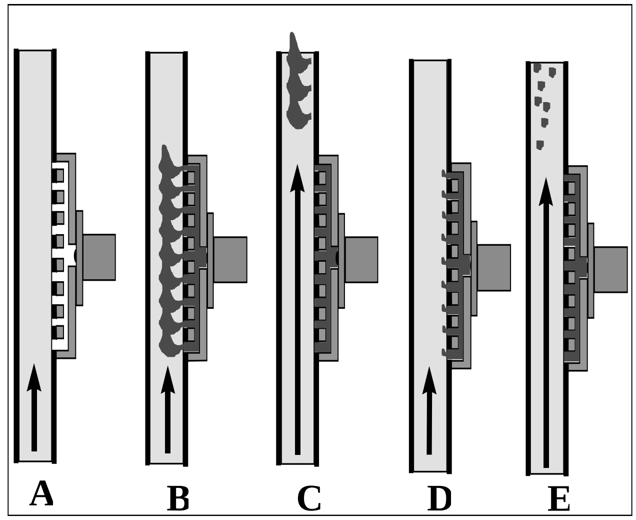

Figure 2: Seeding method

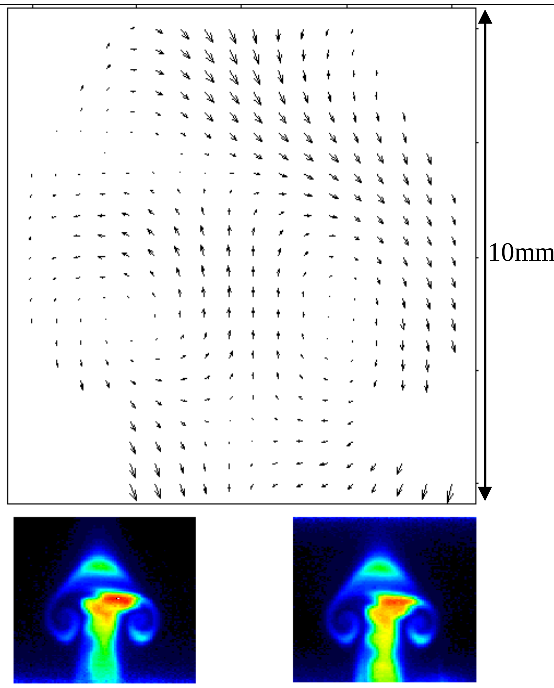

Figure 3: Velocity field and raw LIF (NO) images

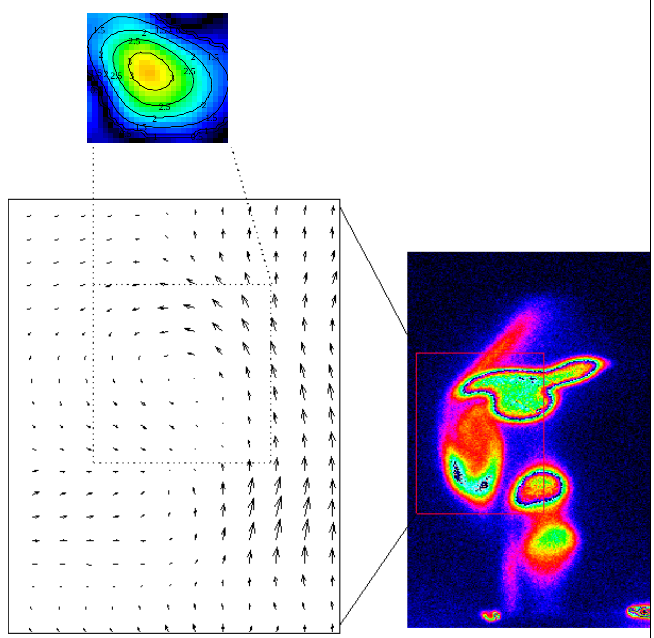

Figure 4: High resolution velocity and vorticity field

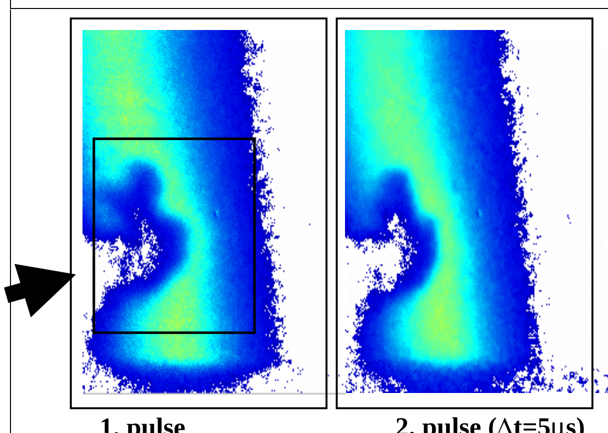

Figure 5: OH double pulse raw images

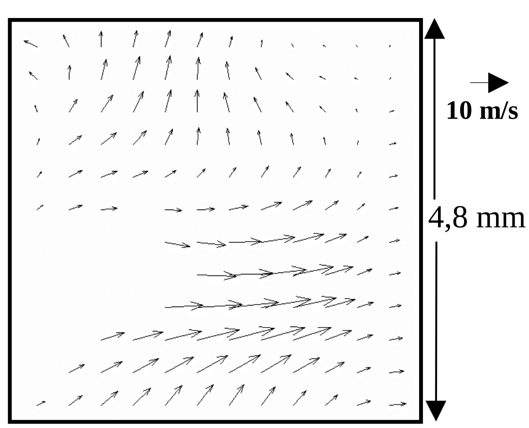

Figure 6: Velocity field from the OH images in Fig. 5