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Volumetric velocimetry in lifted turbulent premixed low-swirl flames

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Abstract
Volumetric velocimetry was successfully performed in lifted turbulent premixed low-swirl flames. A four camera setup in combination with a dual cavity PIV laser was employed to provide data in 20 mm thick sections in both vertical and horizontal directions above the burner. From four simultaneous views of the illuminated particles a 3D array of light intensity discretized over voxels was reconstructed. With two successive reconstructed voxel spaces the three-component velocity vector distribution and the full gradient tensor were calculated by means of the Least Squares Matching (LSM) algorithm. The average volumetric flow field data visualized the bowl shaped low-speed region where the flame can propagate. Instantaneous data captured the complex flow generated by the swirler and the 3D shape of coherent structures in the shear layer surrounding the lifted flame. In the post-flame region the instantaneous flow field displayed an alternating direction of the axial velocity component along the centerline. On average a symmetric stagnation region was identified approximately 60 mm above the nozzle. Large coherent structures identified as parts of a vortex ring were detected downstream of the stagnation region. A local reverse flow through a vortex ring was presented as a possible mechanism for the oscillation along the center axis in the post-flame region and for the instantaneous position of the stagnation plane.

Introduction
The possibility to perform measurements of the 3D velocity field in relatively large volumes has increased the understanding of complex flow fields and the nature of coherent structures. Most combustion devices, e.g. gas turbines, rely on swirling flow fields for flame stabilization and for generation of turbulence to enhance large- and small scale mixing of fuel and oxidizer (maximize fuel-air mixing). Ever more stringent emissions legislation has led to significant changes in modern combustor design and an increased research in new combustion concepts. New designs of the main mixer arrangement can include several annular swirlers e.g. generating co- and counter rotating air flows [1]. Fundamental studies of new designs can be performed in atmospheric test rigs and include investigation of the flow field for cold and reacting cases. A well characterized flow field is also necessary as boundary condition and for validation of Large Eddy Simulations (LES). To characterize such flow fields in detail requires advanced techniques such as volumetric or tomographic flow field measurements.

Stereo-PIV (2D, 3 velocity components) and when possible dual-plane stereo-PIV can be used as first step to investigate complex flows [2]. Different techniques have been explored to gain access to the full 3D flow field. A natural extension of the planar techniques is based on a scanning-light sheet capturing information in multiple-planes with a speed so that the flow can be considered frozen during one sweep [3]. This approach requires costly high-speed systems to image a sufficient number of planes over the volume. An alternative so called tomographic approach is to illuminate the entire volume and image the entire volume (seeding particles in the volume) at once, from several different views simultaneously [4]. From the simultaneous views of the illuminated particles a 3D array of light intensity discretized over voxels is reconstructed. With two exposures separated in time the intensities representing the particles in the volume can then be analyzed by means of e.g. an iterative algorithm to calculate the three-component velocity vector distribution over the measurement volume [5][6][7].

Specific Objectives
In the present study volumetric flow field measurements were applied to study turbulent low-swirl lean premixed methane/air flames. Various versions of the low-swirl burner have been used in several research groups to study the fundamental structure of turbulent premixed flames. Characteristic for the low-swirl flames is the diverging flow field creating a low-speed region where the flame can propagate. Combined with an interaction of the flame with coherent structures emanating from the nozzle the flame dynamic is complex. In a joint LES and single-shot PIV/OH PLIF study [11][12] it was found that the large scale structures generated in the inner shear layer could be responsible for the flame to be stabilized at a relatively low height. The lack of data capturing gradients out of the measurement plane has also limited earlier analysis. This has motivated the present investigation in which we perform volumetric flow field measurements in two different flame conditions.

Experimental Set-up and Methods
To generate the low-swirl flame the burner set-up presented in previous work performed at Lund University was used [10][11][13]. An overview of the burner design is shown in Figure 1a. The low-swirl flow is created by an outer annular swirler where ~60 % by volume of the mixture passes, with eight swirl-vanes, in combination with an inner perforated plate that allows for about 40% by volume of the mixture to pass
through, see Figure 1b. After passing the swirler/perforated plate the premixed methane and air mixture of equivalence ratio 0.62 discharges through a nozzle (diameter of 50 mm) into a co-flow of air. The resulting outflow from the nozzle has an inner low velocity non-swirling region ($X < 10$ mm) and an outer region with higher axial and tangential velocities. The investigated turbulent flames are categorized in the laminar flamelet (leading edge of the flame) and the distributed reaction-zone regimes (typically at the trailing edge of the flame) of the turbulent premixed flame regime diagram. The low-swirl flames have previously been investigated in several publications [10-14].

A volumetric velocimetry system (Dantec Dynamics) was employed to provide data in 20 mm thick sections in both vertical and horizontal directions above the burner. The measurement system consists of four cameras with a resolution of 4 Megapixels (FlowSense EO 4M), mounted on Scheimpflug adaptors to ensure the overlapping of the different depth-of-fields. A dual cavity PIV laser was used for illumination. To ensure that the measurement volume was imaged with the same resolution by all the cameras, a cross like camera setup arrangement was chosen. Moreover, the cameras were facing the illumination source so that the light scattered from the seeding particles was received in forward scattering. The opening angle between the cameras was set to about 110 degrees, ensuring an optimum tomographic reconstruction quality [4]. The optical arrangement around the lifted flame is shown in Figure 2.

The measurement volume was imaged through 60 mm lenses at a working distance of about 450 mm. According to diffraction-limited optics, the depth of field $\Delta z$ of the optical setup can be calculated using the following equation:

$$
\Delta z = \frac{4.88 \cdot \lambda \cdot f^2}{\#^2} \left(1 + \frac{1}{M}\right)^2
$$

with $M$ being the magnification, $\lambda$ the illumination wavelength and $\#$ the numerical aperture of the lens. Therefore, a $\#$ of 11 was chosen giving a depth-of-field of 20 mm and ensuring that the light reaching the camera sensor is significant.

Dedicated illumination optics was used to create a ~20 mm thick light sheet across the burner and illuminating the seeding particles in the volume. As the reader can notice, the illumination was optimized for the depth-of-field, ensuring that the imaged particles are in focus. The effective measurement volume was approximately 50x45x20 mm$^3$ with the presented setup. A schematic diagram of the experimental setup is shown in Figure 3. The camera system was calibrated by traversing and imaging a target in eight planes over the depth-of-field.
From the four camera views (see example in Figure 4), the particles positions were reconstructed via a tomographic technique in an array of typically 500x440x300 voxels. Two successive reconstructed voxel spaces were then analyzed by means of the Least Squares Matching (LSM) algorithm, returning the three-component velocity vector distribution as well as the full gradient tensor over the measurement volume (Figure 5). See Westfeld et al. [7], Kitzhofer et al. [6], Kitzhofer et al. [9] and Jaunet et al. [8], for more precise information on the LSM algorithms.

Results and Discussion

Two methane/air flames are investigated both with an equivalence ratio of 0.62. The Reynolds numbers (Re) based on the bulk flow velocity (6.2 and 9.3 m/s) and diameter at the burner exit are about Re=20 000, and Re=30 000. An overview of the flow field and a schematic flame position is given in Figure 6. Mean flame position at the centerline is 32 mm above the nozzle for Re=20 000, and 30 mm for Re=30 000 [11]. Characteristics for the low-swirl flames are that the interaction between turbulence eddies and the chemical reactions occur in both the laminar flamelet (leading edge of flame) and the distributed reaction-zone regimes (trailing edge of flame) of the turbulent premixed flame regime diagram.

The volumetric flow field data in Figure 7 clearly visualizes the bowl shaped low-speed region created by the diverging flow field. The corresponding cold flow field (not shown) shows a slightly slower divergence of the flow [11]. The contours in Figure 7 show how the axial flow slows down with height along the center line. In mean the tangential component (swirl) is close to zero in the inner part (X<10 mm) of the flow field, see also Figure 6. At the centerline the leading edge of the flame is in mean positioned 32 mm above the nozzle for Re=20 000. This mean flame position is a combination of that the flow has slowed sufficiently (around 1 m/s, [13]) and that the flame is wrinkled by the interacting with large coherent structures and turbulence increasing the fuel consuming flame area [14] and the flame propagation speed.
In Figure 7 below the average flow field in a horizontal section capturing the central part of the flame brush region above the nozzle, is shown (corresponds to the flow field in Figure 7). It can be noted that the average data taken within the flame brush has contributions from both burnt and unburnt regions due to the fluctuation of the flame front position. The inner low-speed region at the mean flame height, Z=32 mm, is visualized by the contours representing the axial velocity (V). Previous work has shown that the signatures of the flow passing the swirler vanes are present as the flow exits the nozzle [12]. The drawn ellipsis in Figure 7 shows that these high-speed regions, following helical paths due to the swirl component, are still found in the flow around the flame region.

The expansion due to the heat release is visualized by the jump in seeding density in the raw images in Figure 4 above. However, even with the expansion in the post-flame region the mean volumetric flow field in Figure 8 visualizes a symmetric stagnation region approximately 60 mm above the nozzle. This is in agreement with the stagnation plane in the overall 2D flow field shown in Figure 6.

In Figure 9 an example of the instantaneous volumetric vector field capturing the inner low-speed region (X<10 mm) and part of the outer region with higher velocities. The shear layer between the inner and outer region origins from the swirler arrangement (Figure 1b) and develops in the downstream direction. Previous simulations (LES) and time-resolved PIV (2D) have shown that coherent structures in the shear layer are emanating from the nozzle and convected downstream [14]. The iso-surfaces in Figure 10 visualize the vorticity magnitude identifying the vortex cores and thus the 3D structure of such coherent structures in the flow. The vortex detection is performed with the Q-criterion [15] utilizing the information from the velocity gradient tensor generated with the LSM algorithm. The interaction between coherent structures and the flame is previously analyzed via LES and modal decomposition of time-resolved flow field data [14]. The results in Petersson et al. [14] indicated how the leading and trailing edge of the flame was pulled radially and upstream by coherent structures with characteristics correlated to the structures presented in Figure 10. A result of the interaction between the flame and coherent structures is that the flame in average will be positioned at a much lower height above the nozzle.
then indicated by the mean flow field and its fluctuations (root mean square values).

Figure 10. Instantaneous flow field with iso-surfaces visualizing complex coherent structures surrounding the inner low-speed region.

The instantaneous flow field and large coherent structures in the post-flame region are displayed in Figure 11 and 12. A reverse axial flow in the center between the surrounding structures is clearly shown above the instantaneous stagnation region 70 mm above the burner in Figure 11. The direction of rotation of the large structure correlates with the created reverse flow in the center for Y > 75 mm i.e. above the stagnation plane. This is further discussed in connection with Figure 12 below.

Figure 11. Instantaneous flow field with large coherent structures positioned in the stagnation region. The iso-surfaces represent the vorticity magnitude identifying the vortex cores. The rotation direction of the vortex cores is the same as illustrated in Figure 12.

In Figure 12 the stagnation region is at a lower position and only just captured in the lower part of the image. A part of a large vortex structure (compare with Figure 11), assumed to be half of a vortex ring, positioned in the X-Z plane, is by its rotation guiding the flow radially inwards, Y=70 mm, and upstream (reverse axial flow) along the center axis towards the created instantaneous stagnation region at Y=50 mm. The direction of rotation of the large coherent structures in both Figure 11 and 12 is consistent with that of a vortex ring with an upstream rotation direction towards the center axis. Thus this large vortex structure is contributing to an upstream (reverse) transport of fluid (for Y > 50 mm) and involved in the formation of instantaneous stagnation regions at different heights with time. Note that the diverging flow field due to the swirl is the primary mechanism for the stagnation. It can be mentioned that Therkelsen et al. [16] reported shedding of vortex rings from the nozzle rim in an enclosed version of the low-swirl burner. These vortex rings, detected by phase-resolved PIV, was found to be convected in the outer shear layer leaving a dominant frequency peak in the acoustic and flame oscillation spectra [16].

Figure 12. Instantaneous flow field and large coherent structure in the post-flame region. The iso-surfaces represent the vorticity magnitude identifying the vortex cores. The rotation direction of the vortex cores is consistent with a vortex ring.

An alternative view of structures active around the stagnation region is shown in Figure 13. With only one plane of vectors plotted and the volume tilted in the Z-direction details of coherent structures in the measurement volume can be studied. The instantaneous structures in the upper part of Figure 13 are complex, partly including segments with double vortex cores, which can be an effect of merging of interacting vortices. The rotation direction of the two upper structures in Figure 13 is the same as illustrated in Figure 12, here further visualized by the local vector field.
Figure 13. Details of coherent structures active around the stagnation region. Only one plane of vectors in the measurement volume is presented to increase visibility. The iso-surfaces represent the vorticity magnitude identifying the vortex cores.

Conclusions

Volumetric velocimetry was successfully performed in lifted turbulent premixed low-swirl flames. With the four camera system the reconstruction of the densely seeded regions was achieved with high quality. The mean flow field captures the inner low-speed region housing the flame and the stagnation region in the post-flame region. The complex flow generated by the swirler and nozzle including the coherent structures surrounding the flame region and its influence on the flame dynamics have been better understood. Large coherent structures identified as parts of a vortex ring were detected downstream of the stagnation region. A local reverse flow through the center of a vortex ring was presented as a possible mechanism for the oscillation along the center axis in the post-flame region and for determining the instantaneous position of the stagnation plane.

Planned future work includes tests with combined volumetric flow field and 3D flame surface visualization to capture the flame flow interaction in 3D.

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References


